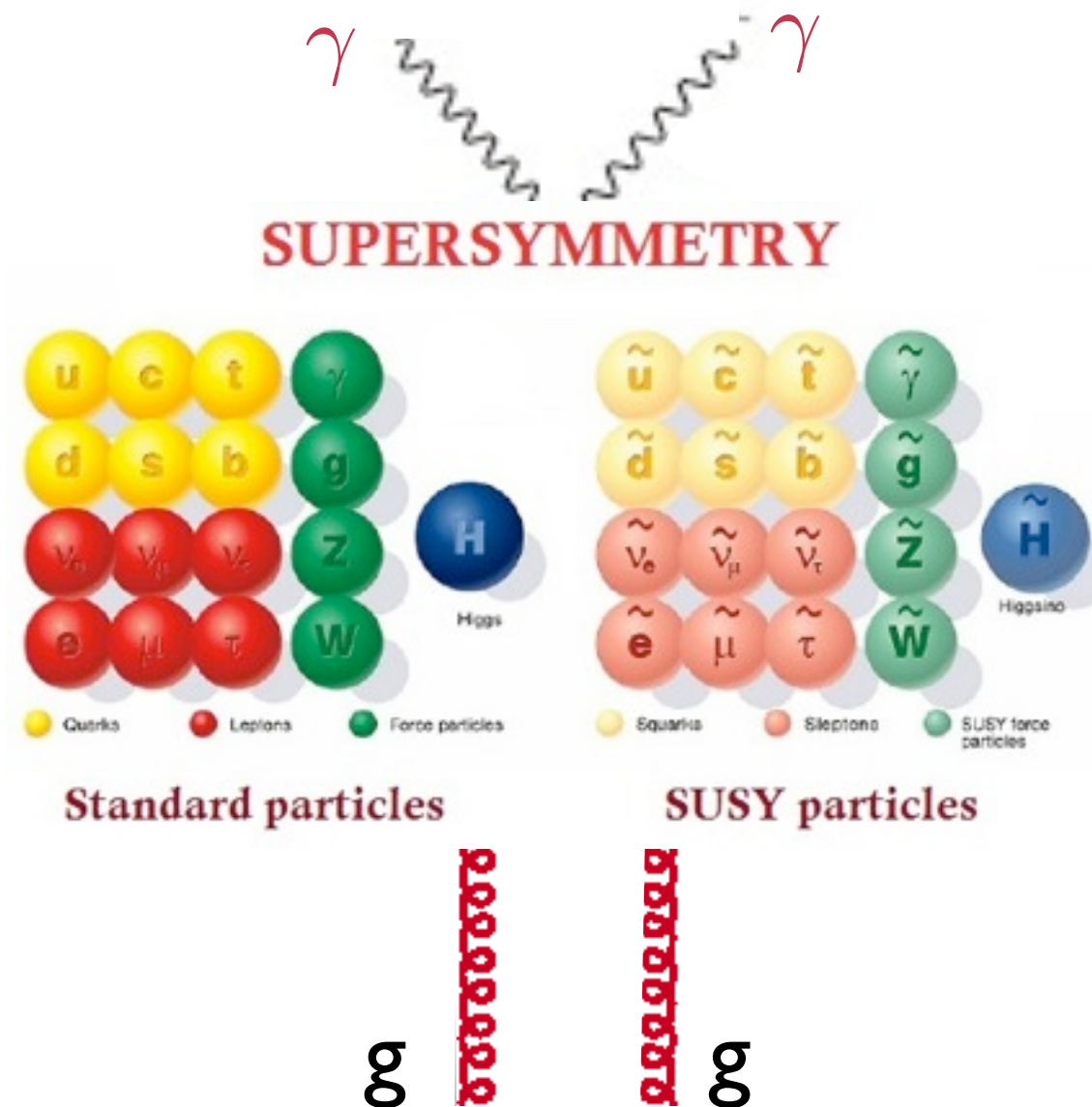
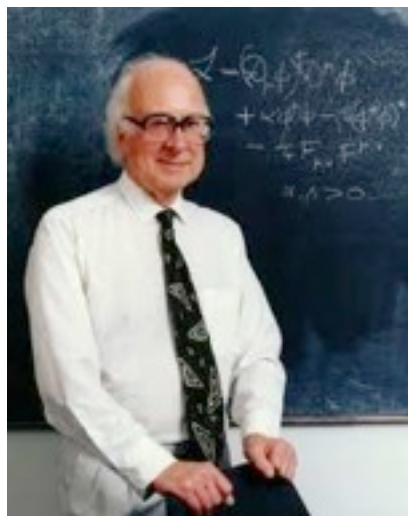


MSSM Higgs Search Benchmarks after the 125 GeV Higgs Discovery



Carlos E.M. Wagner
KICP and EFI, Univ. of Chicago
HEP Division Argonne National Lab

Snowmass EF workshop, Brookhaven National Lab, 04.04.13



Higgs Discovery :

Implications for Low Energy Supersymmetry

- Particle Properties consistent with SM-like Higgs : Lightest CP-even Higgs scalar tends to behave in such a way.
- Measured mass well within the range predicted in the MSSM for stop masses larger than a few hundred GeV and sizable mixing parameter
- Sizable deviations from the SM Higgs couplings still possible, what can be obtained in the MSSM for either small values of the third generation particle masses or for relatively small values of the CP-odd Higgs mass.
- For large values of the ratio of vacuum expectation value the Higgs sector properties deviate from the type II two Higgs doublet one, due to the presence of non-holomorphic couplings to fermions. Ratio of bottom to tau coupling deviates from the SM one.

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A

* $\tan \beta$

* the top quark mass

* the stop masses and mixing

$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} \mathbf{m}_Q^2 + \mathbf{m}_t^2 + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}_U^2 + \mathbf{m}_t^2 + \mathbf{D}_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t . [and on sbottom/stau sectors for large $\tan\beta$]

For moderate to large values of $\tan \beta$ and large non-standard Higgs masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[\frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left(\frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right) (\tilde{X}_t t + t^2) \right]$$

$$t = \log(M_{\text{SUSY}}^2 / m_t^2) \quad \tilde{X}_t = \frac{2X_t^2}{M_{\text{SUSY}}^2} \left(1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right)$$

$$\underline{X_t = A_t - \mu / \tan \beta} \rightarrow \text{LR stop mixing}$$

M.Carena, J.R. Espinosa, M. Quiros, C.W.'95

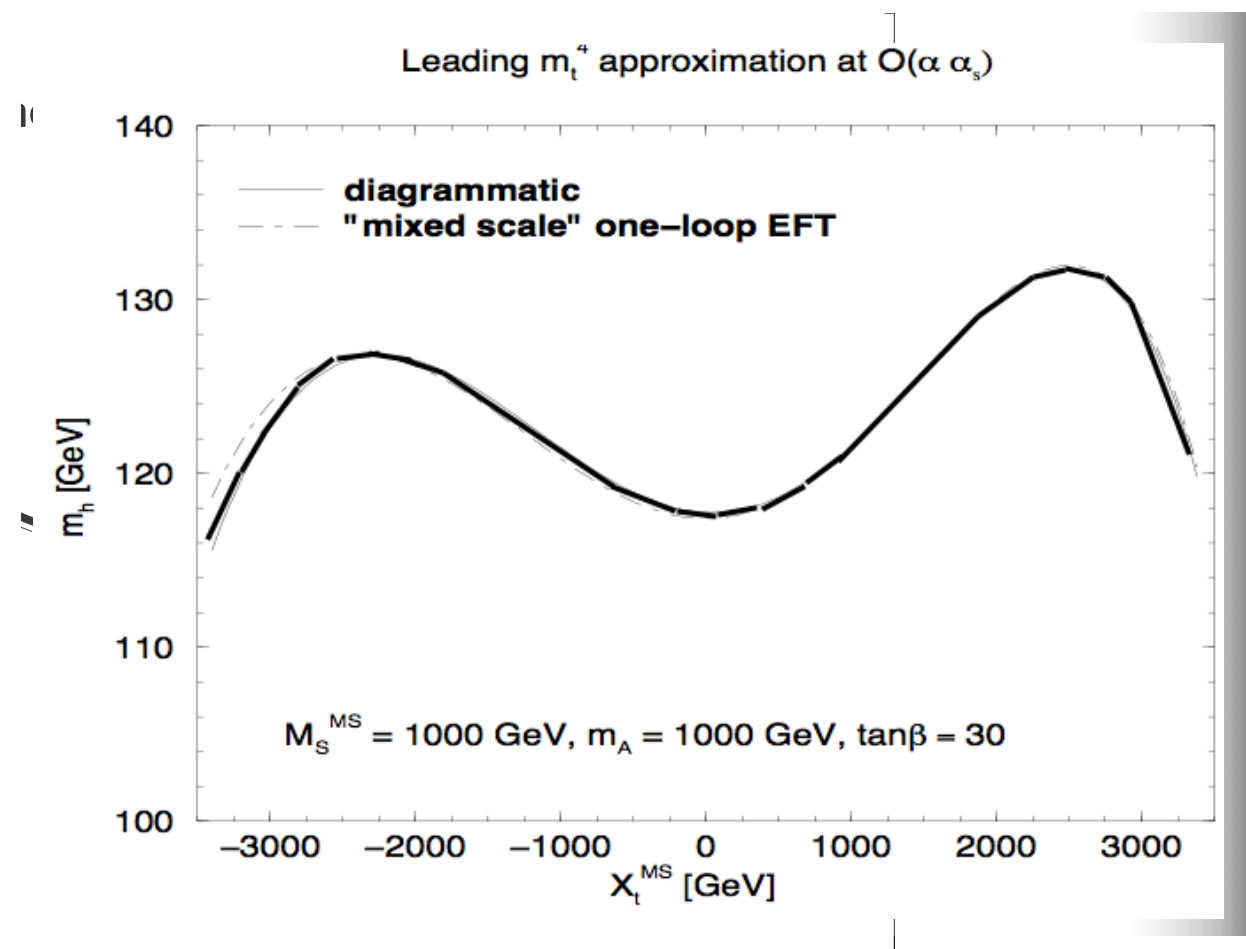
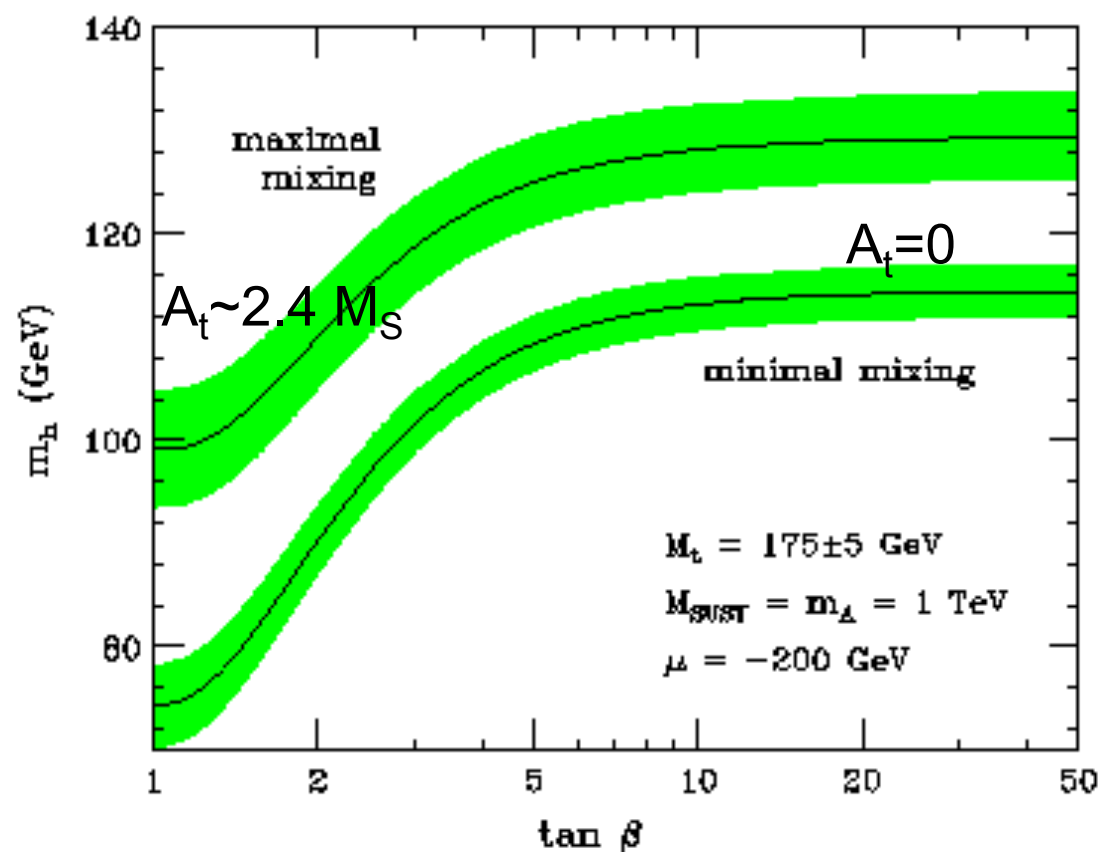
M. Carena, M. Quiros, C.W.'95

Analytic expression valid for $M_{\text{SUSY}} \sim m_Q \sim m_U$

Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

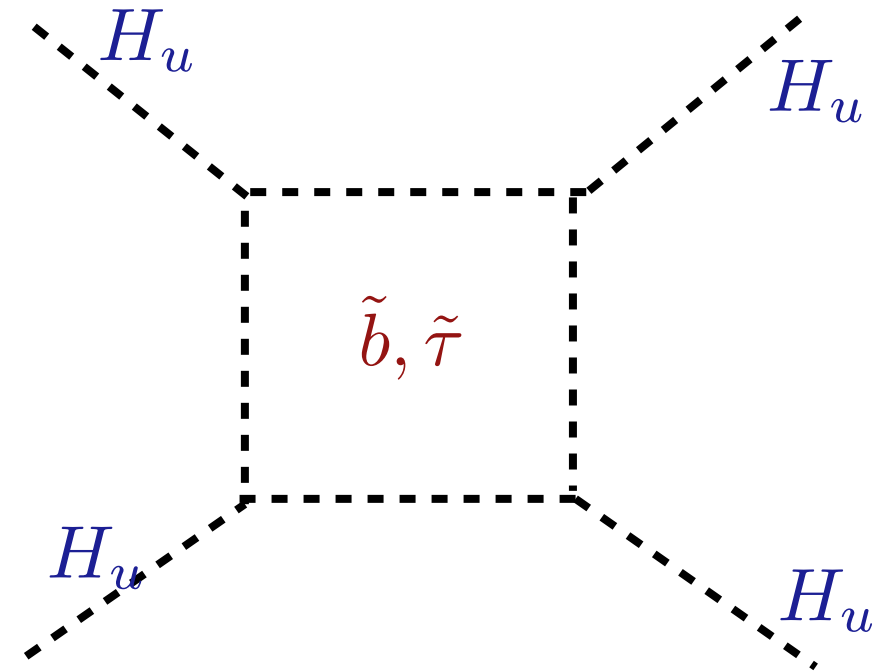


$$X_t = A_t - \mu / \tan \beta, \quad X_t = 0 : \text{No mixing}; \quad X_t = \sqrt{6} M_S : \text{Max. Mixing}$$

Large $\tan \beta$ corrections

Corrections from the sbottom sector :
Negative contributions to the Higgs mass

$$\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2} \frac{\mu^4}{M_{\text{SUSY}}^4}$$



$$h_b \simeq \frac{m_b}{v \cos \beta (1 + \tan \beta \Delta h_b)}$$

Similar negative corrections, often ignored,
appear from the stau sector

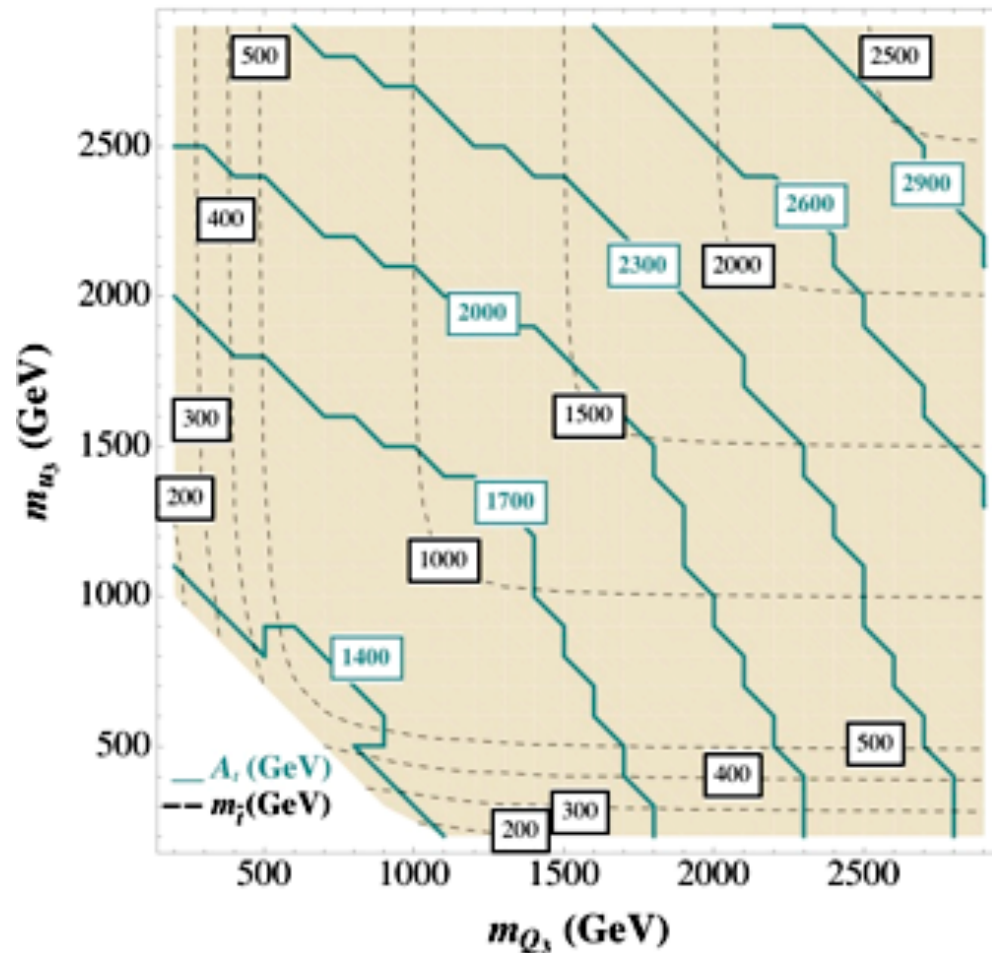
$$\Delta m_h^2 \simeq -\frac{h_\tau^4 v^2}{48\pi^2} \frac{\mu^4}{M_{\tilde{\tau}}^4},$$

$$h_\tau \simeq \frac{m_\tau}{v \cos \beta (1 + \tan \beta \Delta h_\tau)}$$

Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

A_t and $m_{\tilde{t}}$ for $124 \text{ GeV} < m_h < 126 \text{ GeV}$ and $\tan \beta = 10$



Large stop sector mixing

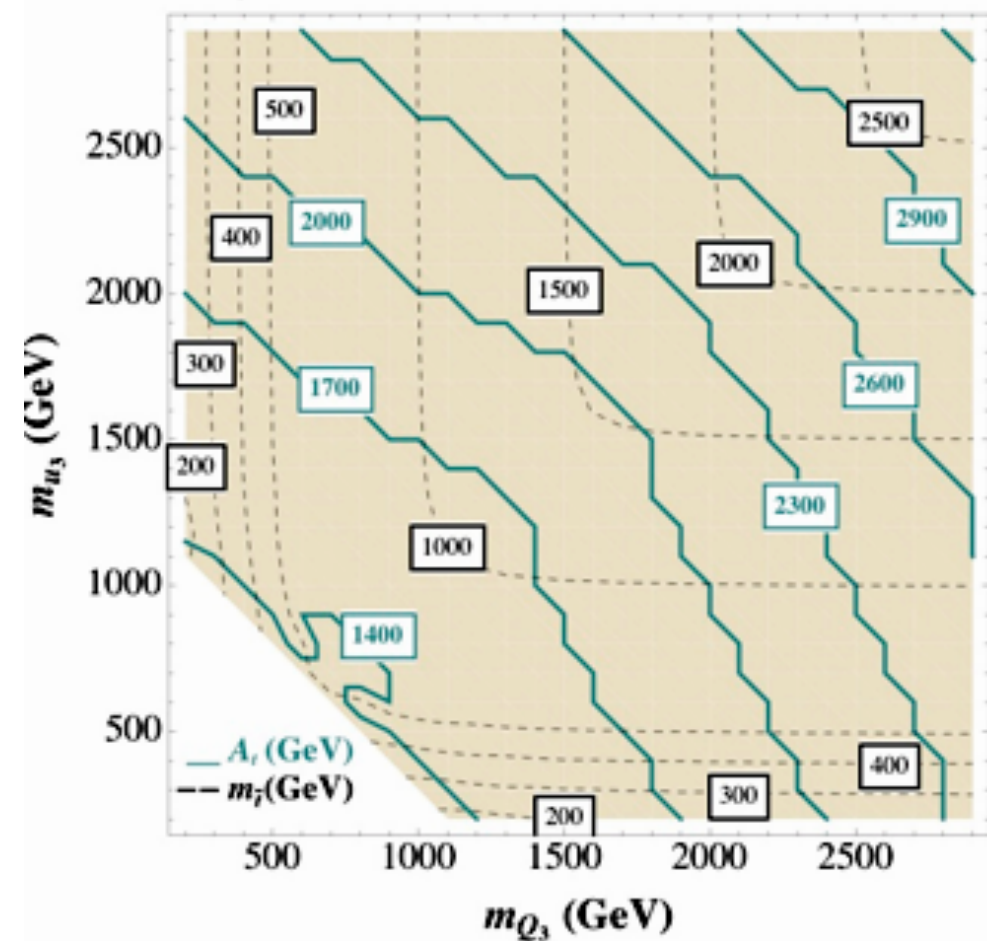
$$A_t > 1 \text{ TeV}$$

No lower bound on the lightest stop

One stop can be light and the other heavy
or

in the case of similar stop soft masses.
both stops can be below 1 TeV

A_t and $m_{\tilde{t}}$ for $124 \text{ GeV} < m_h < 126 \text{ GeV}$ and $\tan \beta = 60$



Intermediate values of tan beta lead to
the largest values of m_h for the same values
of stop mass parameters

At large tan beta, light staus/sbottoms can decrease
 m_h by several GeV's via Higgs mixing effects
and compensate tan beta enhancement

Light stop coupling to the Higgs

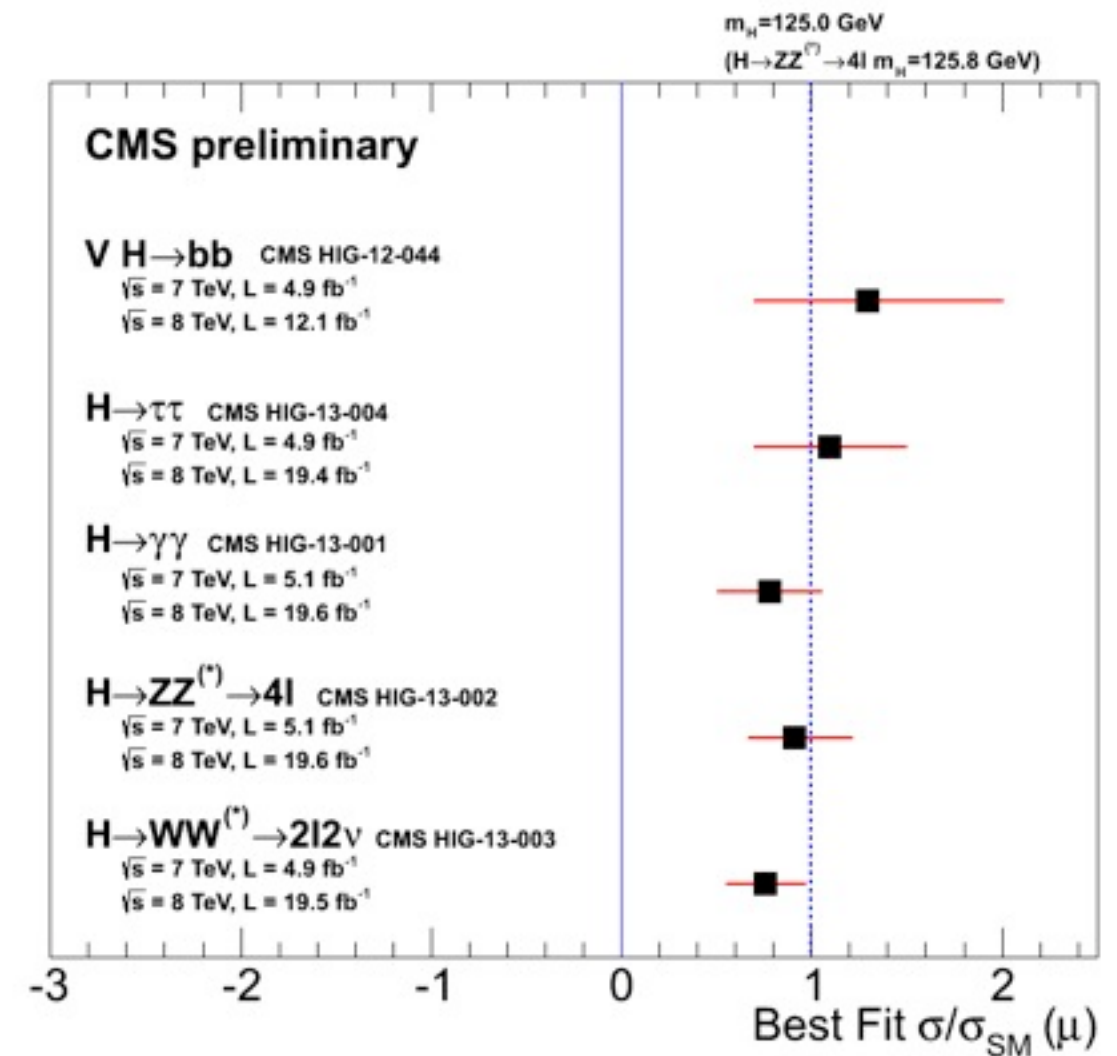
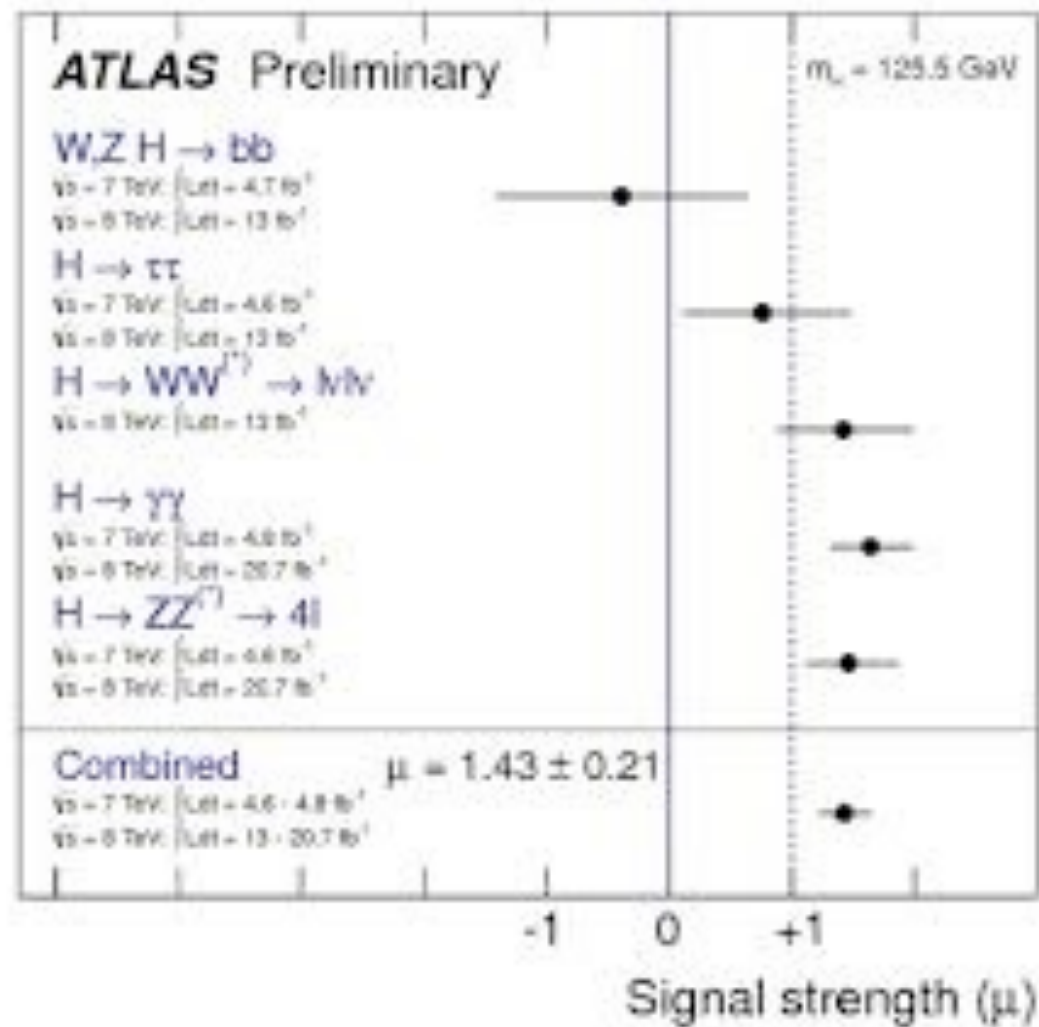
$$m_Q \gg m_U; \quad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2} \right)$$

Lightest stop coupling to the Higgs approximately vanishes for $X_t \simeq m_Q$

Higgs mass pushes us in that direction

Modification of the gluon fusion rate milder due to this reason.

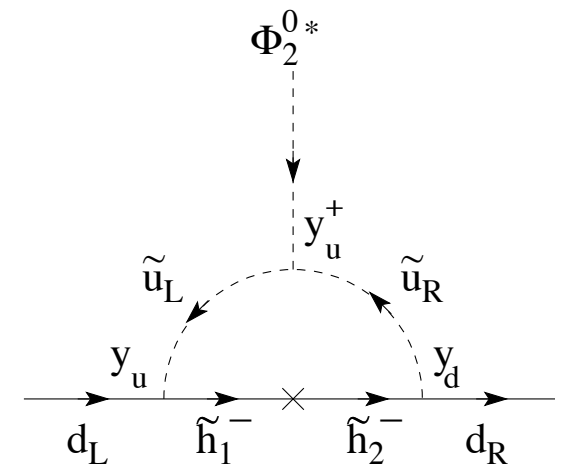
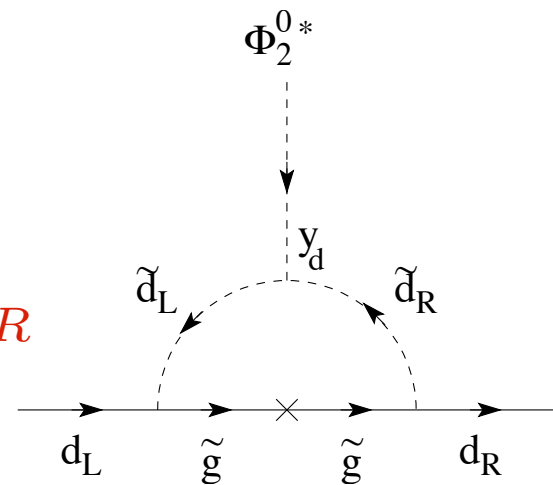
Large Variations of Higgs couplings are still possible



Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to **both Higgs** fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$



- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan \beta \right)$$

$$\boxed{\tan \beta = \frac{v_2}{v_1}}$$

$$\frac{\Delta_b}{\tan \beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu / \tan \beta \simeq A_t \quad \Delta_b = (E_g + E_t h_t^2) \tan \beta$$

Resummation : Carena, Garcia, Nierste, C.W'00

Couplings to Fermions and Gauge Bosons

Down-type Fermions

$$g_{hbb,h\tau\tau} = -h_{b,\tau} \sin \alpha + \Delta h_{b,\tau} \cos \alpha$$

$$g_{hbb,h\tau\tau} = -\frac{m_{b,\tau} \sin \alpha}{v \cos \beta (1 + \Delta_{b,\tau})} \left(1 - \frac{\Delta_{b,\tau}}{\tan \beta \tan \alpha} \right)$$

Up-type Fermions

$$g_{htt} = \frac{m_t \cos \alpha}{v \sin \beta}$$

Gauge Bosons

For moderate values of m_A and $\tan \beta$,
the top and W, Z couplings go fast to SM values

$$g_{hWW,hZZ} \simeq \sin(\alpha - \beta)$$

$$\cos(\alpha - \beta) \simeq \frac{M_h^2}{M_A^2 \tan \beta}$$

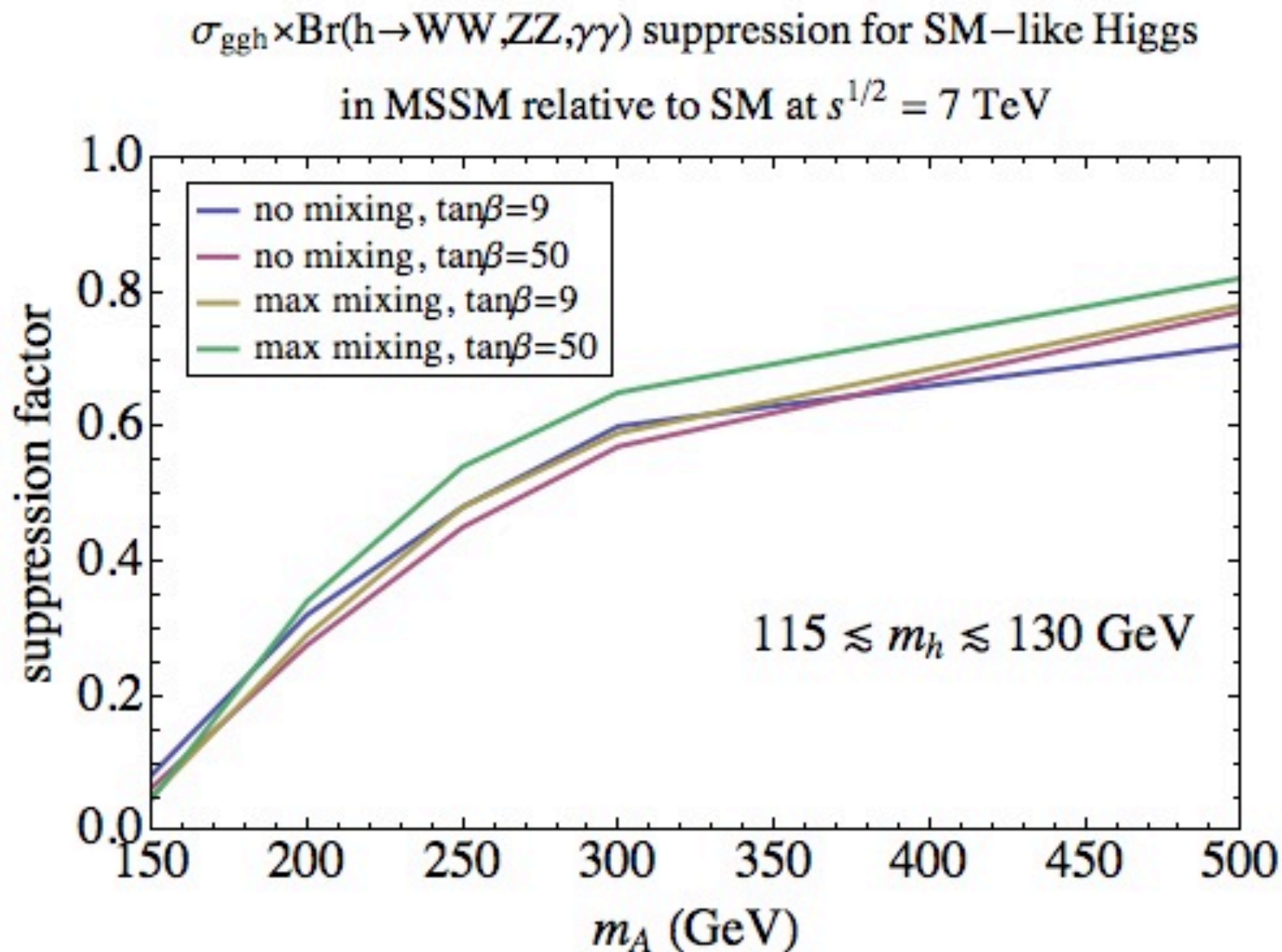
$$\frac{\cos \alpha}{\sin \beta} \simeq \sin(\beta - \alpha)$$

$$\frac{|\sin \alpha|}{\cos \beta} \simeq 1 + \frac{M_h^2}{M_A^2} + \text{loop corr.}$$

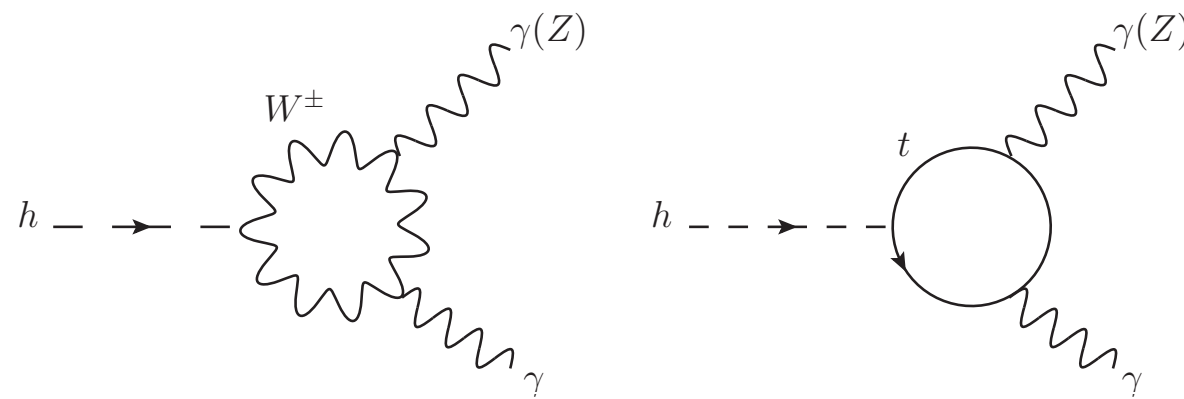
Suppression Factors at the LHC

If loop corrections are small

[M. Carena, P. Draper, T. Liu, C. W., arXiv:1107.4354](#)



Dominant Contributions to the Diphoton Width in the Standard Model



Similar corrections appear from other scalar, fermion or vector particles. Clearly, similarly to the top quark, chiral fermions tend to reduce the vector boson contributions

Higgs Diphoton Decay Width in the SM

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128 \sqrt{2} \pi^3} \left| A_1(\tau_w) + N_c Q_t^2 A_{1/2}(\tau_t) \right|^2 \quad \tau_i \equiv 4m_i^2/m_h^2$$

A. Djouadi'05

For particles much heavier than the Higgs boson

$$A_1 \rightarrow -7, \quad N_c Q_t^2 A_{1/2} \rightarrow \frac{4}{3} N_c Q_t^2 \simeq 1.78, \quad \text{for } N_c = 3, Q_t = 2/3$$

In the SM, for a Higgs of mass about 125 GeV

$$m_h = 125 \text{ GeV} : A_1 = -8.32, \quad N_c Q_t^2 A_{1/2} = 1.84$$

Dominant contribution from W loops. Top particles suppress by 40 percent the W loop contribution. One can rewrite the above expression in terms of the couplings of the particles to the Higgs as :

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024 \pi^3} \left| \frac{g_{hWW}}{m_W^2} A_1(\tau_w) + \frac{2g_{ht\bar{t}}}{m_t} N_c Q_t^2 A_{1/2}(\tau_t) + N_c Q_s^2 \frac{g_{hSS}}{m_S^2} A_0(\tau_S) \right|^2$$

Inspection of the above expressions reveals that the contributions of particles heavier than the Higgs boson may be rewritten as

$$\mathcal{L}_{h\gamma\gamma} = -\frac{\alpha}{16\pi} \frac{h}{v} \left[\sum_i 2b_i \frac{\partial}{\partial \log v} \log m_i(v) \right] F_{\mu\nu} F^{\mu\nu} \quad \left\{ \begin{array}{ll} b = \frac{4}{3} N_c Q^2 & \text{for a Dirac fermion ,} \\ b = -7 & \text{for the } W \text{ boson ,} \\ b = \frac{1}{3} N_c Q_S^2 & \text{for a charged scalar .} \end{array} \right.$$

where in the Standard Model

$$\frac{g_{hWW}}{m_W^2} = \frac{\partial}{\partial v} \log m_W^2(v) , \quad \frac{2g_{ht\bar{t}}}{m_t} = \frac{\partial}{\partial v} \log m_t^2(v)$$

This generalizes for the case of fermions with contributions to their masses independent of the Higgs field. The couplings come from the vertex and the inverse dependence on the masses from the necessary chirality flip (for fermions) and the integral functions.

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi} \frac{h}{v} \left[\sum_i b_i \frac{\partial}{\partial \log v} \log \left(\det \mathcal{M}_{F,i}^\dagger \mathcal{M}_{F,i} \right) + \sum_i b_i \frac{\partial}{\partial \log v} \log \left(\det \mathcal{M}_{B,i}^2 \right) \right] F_{\mu\nu} F^{\mu\nu}$$

M. Carena, I. Low, C.W., arXiv:1206.1082, Ellis, Gaillard, Nanopoulos'76, Shifman, Vainshtein, Voloshin, Zakharov'79

Similar considerations apply to the Higgs gluon coupling

Two Scalars with Mixing

Similar to light stau scenario,

M. Carena, S. Gori, N. Shah, C.W., arXiv:1112.3336,

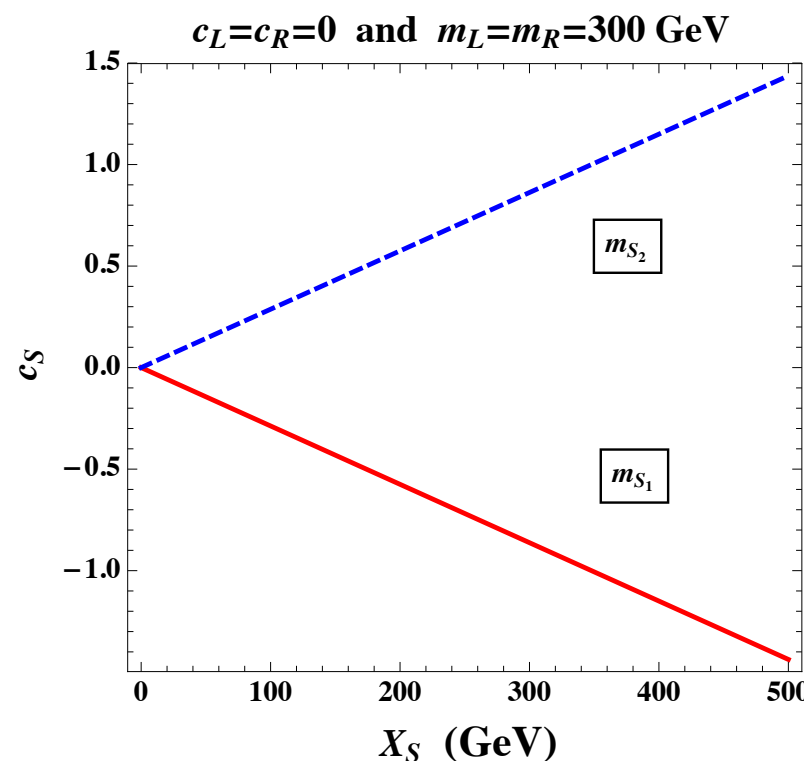
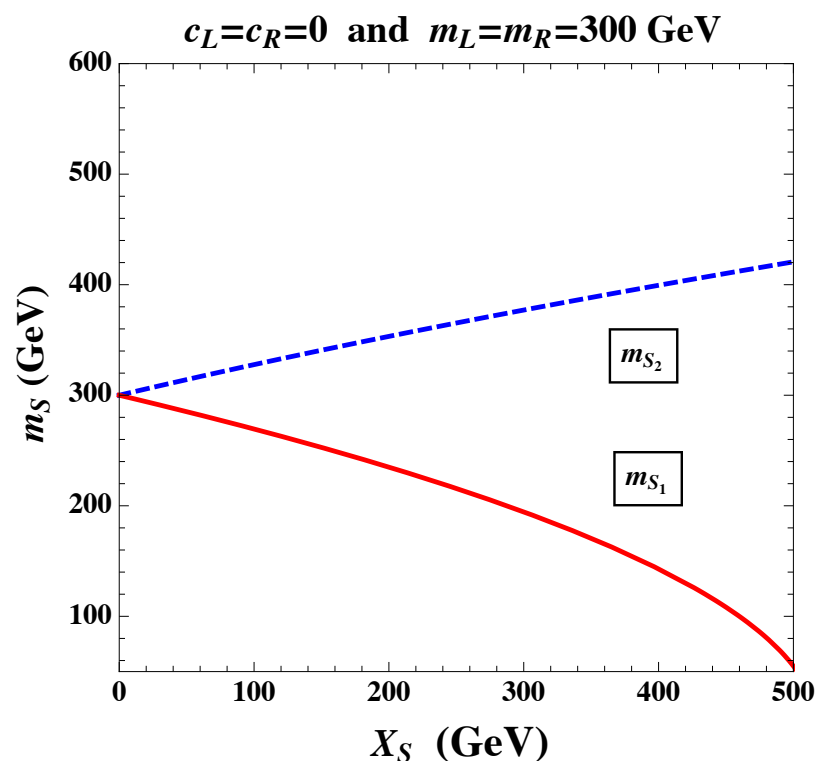
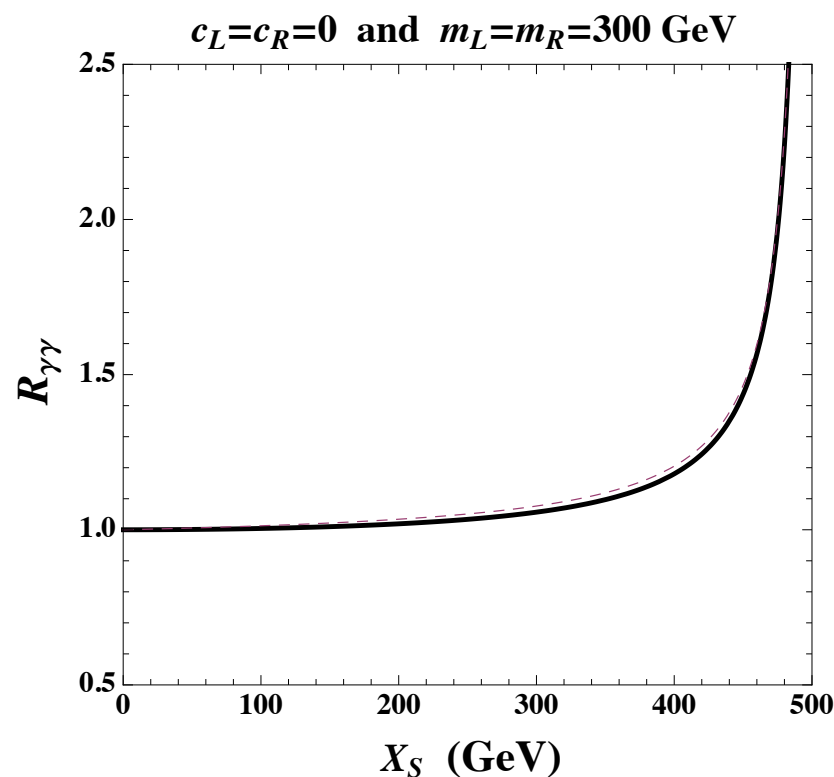
M. Carena, S. Gori, N. Shah, C.W., L.T. Wang, arXiv:1205.5842

$$\mathcal{M}_S^2 = \begin{pmatrix} \tilde{m}_L(v)^2 & \frac{1}{\sqrt{2}}vX_S \\ \frac{1}{\sqrt{2}}vX_S & \tilde{m}_R(v)^2 \end{pmatrix}$$

$$\frac{\partial \log(\text{Det} M_S^2)}{\partial v} \simeq - \frac{X_S^2 v}{m_{S_1}^2 m_{S_2}^2}$$

Negative Effective
Coupling of lightest
scalar

Large mixing and small value of the
lightest scalar mass leads to enhancement
of the diphoton amplitude

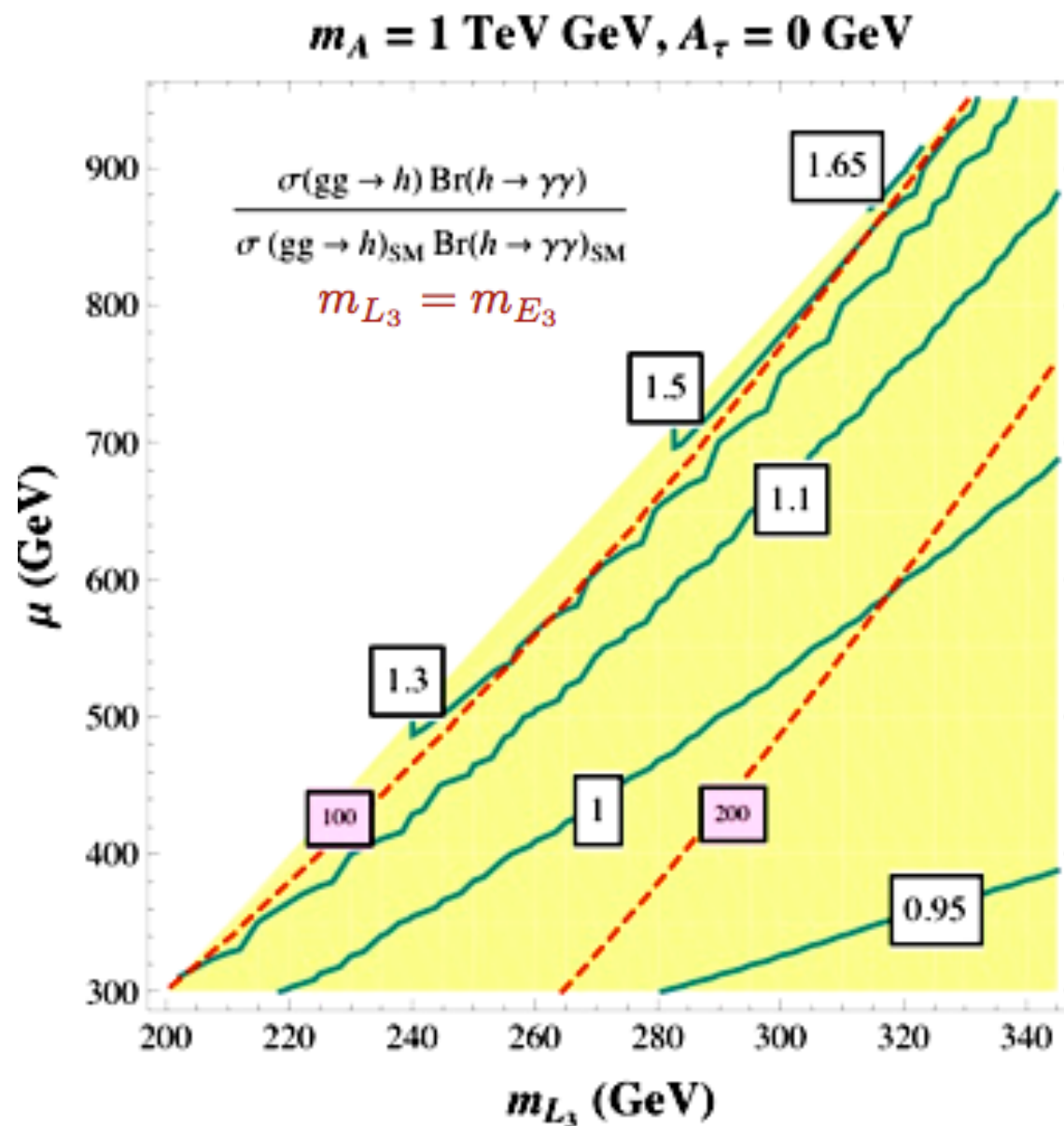


Lightest scalar, with
mass below 200 GeV
gives the dominant
contribution in this
case.

M. Carena, I. Low, C.W., arXiv:1206.1082

Higgs Decay into two Photons in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



$$\mathcal{M}_{\tilde{\tau}}^2 \simeq \begin{bmatrix} m_{L_3}^2 + m_{\tilde{\tau}}^2 + D_L & h_\tau v(A_\tau \cos \beta - \mu \sin \beta) \\ h_\tau v(A_\tau \cos \beta - \mu \sin \beta) & m_{E_3}^2 + m_{\tilde{\tau}}^2 + D_R \end{bmatrix}$$

Light staus with large mixing

[sizeable μ and $\tan \beta$]:

**→ enhancement of the
Higgs to di-photon decay rate**

$$\delta \mathcal{A}_{h\gamma\gamma} / \mathcal{A}_{h\gamma\gamma}^{\text{SM}} \simeq -\frac{2 m_\tau^2}{39 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} (m_{\tilde{\tau}_1}^2 + m_{\tilde{\tau}_2}^2 - X_\tau^2)$$

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

For a more generic discussion of modified diphoton width by new charged particles,
see M. Carena, I. Low and C. Wagner, arXiv:1206.1082

Mixing Effects in the CP- even Higgs Sector

- Mixing can have relevant effects in the production and decay rates

$$\mathcal{M}_H^2 = \begin{bmatrix} m_A^2 \sin^2 \beta + M_Z^2 \cos^2 \beta & -(m_A^2 + M_Z^2) \sin \beta \cos \beta + \text{Loop}_{12} \\ -(m_A^2 + M_Z^2) \sin \beta \cos \beta + \text{Loop}_{12} & m_A^2 \cos^2 \beta + M_Z^2 \sin^2 \beta + \text{Loop}_{22} \end{bmatrix}$$

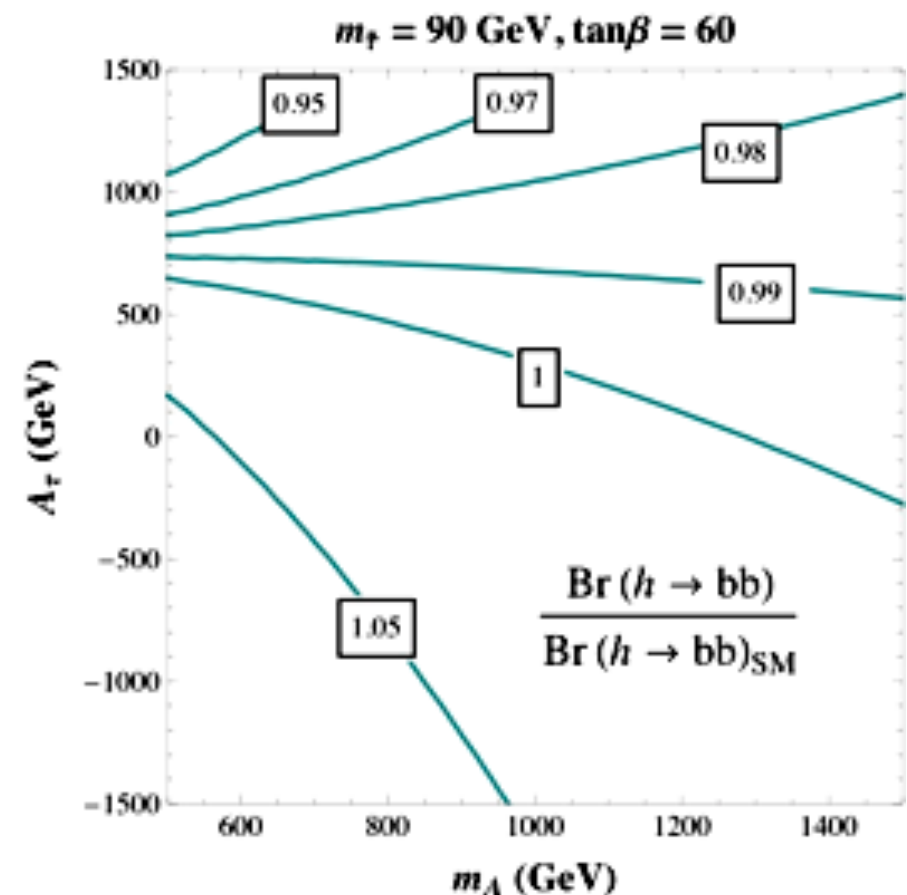
$$\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta} \frac{\mu \bar{A}_t}{M_{\text{SUSY}}^2} \left[\frac{A_t \bar{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\text{SUSY}}^4}$$

effects through radiative corrections
to the CP-even mass matrix
which defines the mixing angle alpha

$$\sin \alpha \cos \alpha = M_{12}^2 / \sqrt{(\text{Tr } M^2)^2 - 4 \det M^2}$$

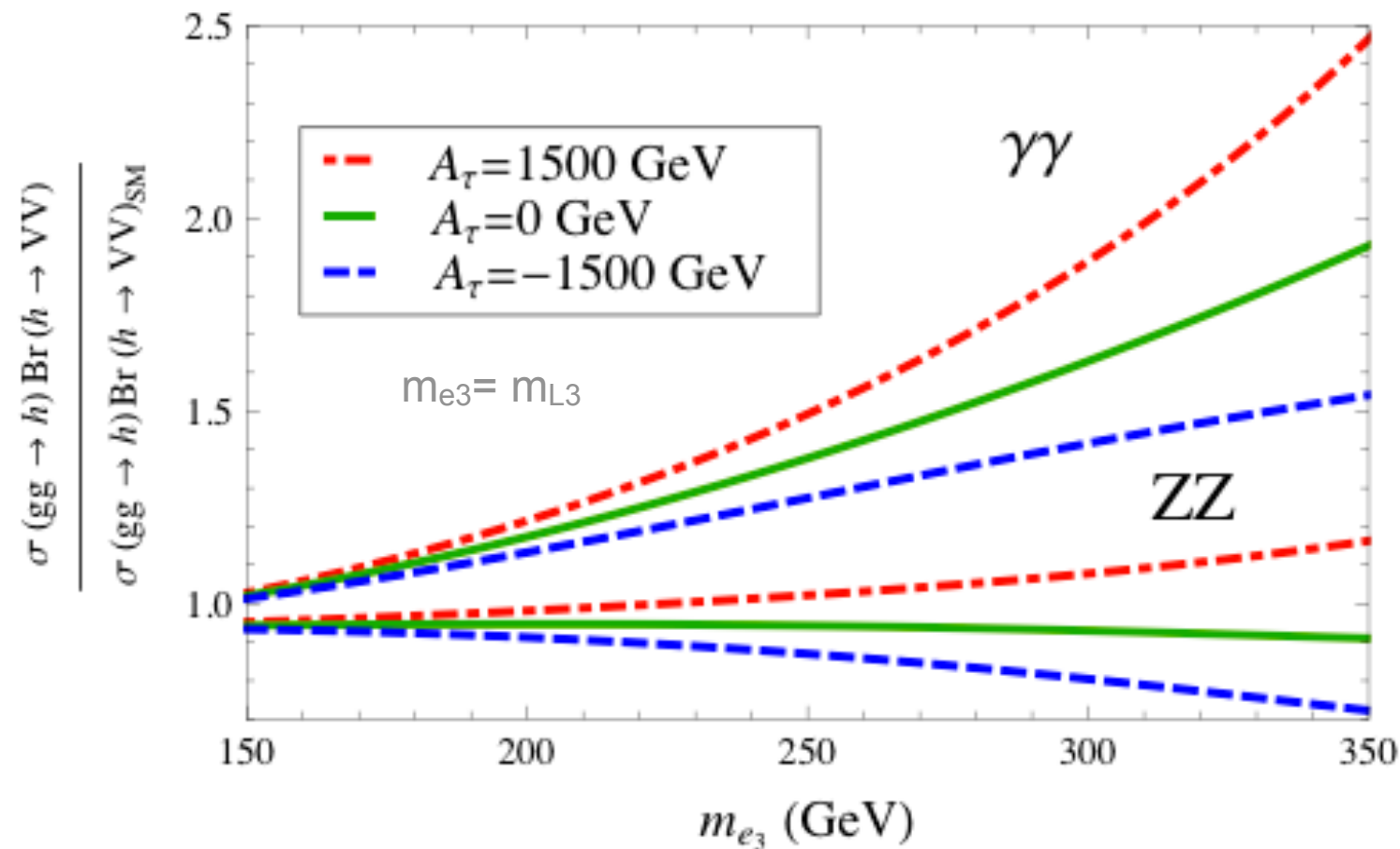
$$h b \bar{b} : -\frac{\sin \alpha}{\cos \beta} \left[1 - \frac{\Delta h_b \tan \beta}{1 + \Delta h_b \tan \beta} \left(1 + \frac{1}{\tan \alpha \tan \beta} \right) \right]$$

Small Variations in the $\text{Br}(H b \bar{b})$ can induce significant variations in the other Higgs Br's



Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T. Wang, arXiv:1205.5842



$m_{\text{Stau}} \sim 90 \text{ GeV}; m_h \sim 125 \text{ GeV}$

Important A_τ induced
radiative corrections to the
mixing angle α that defines
the bottom coupling to Higgs
 $hbb \sim \sin\alpha/\cos\beta$



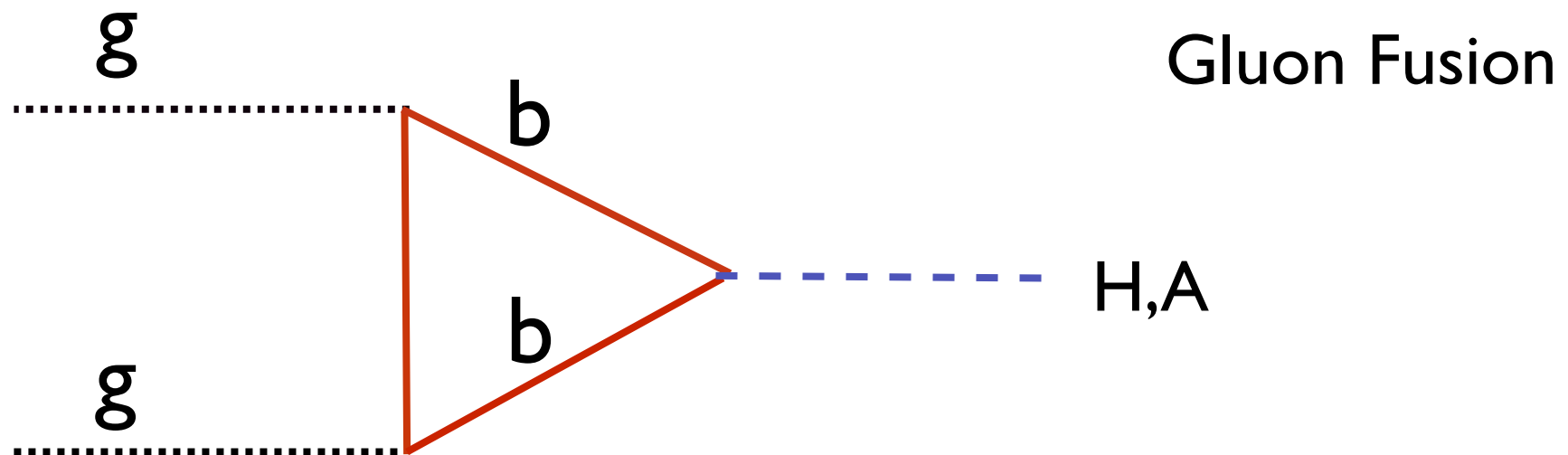
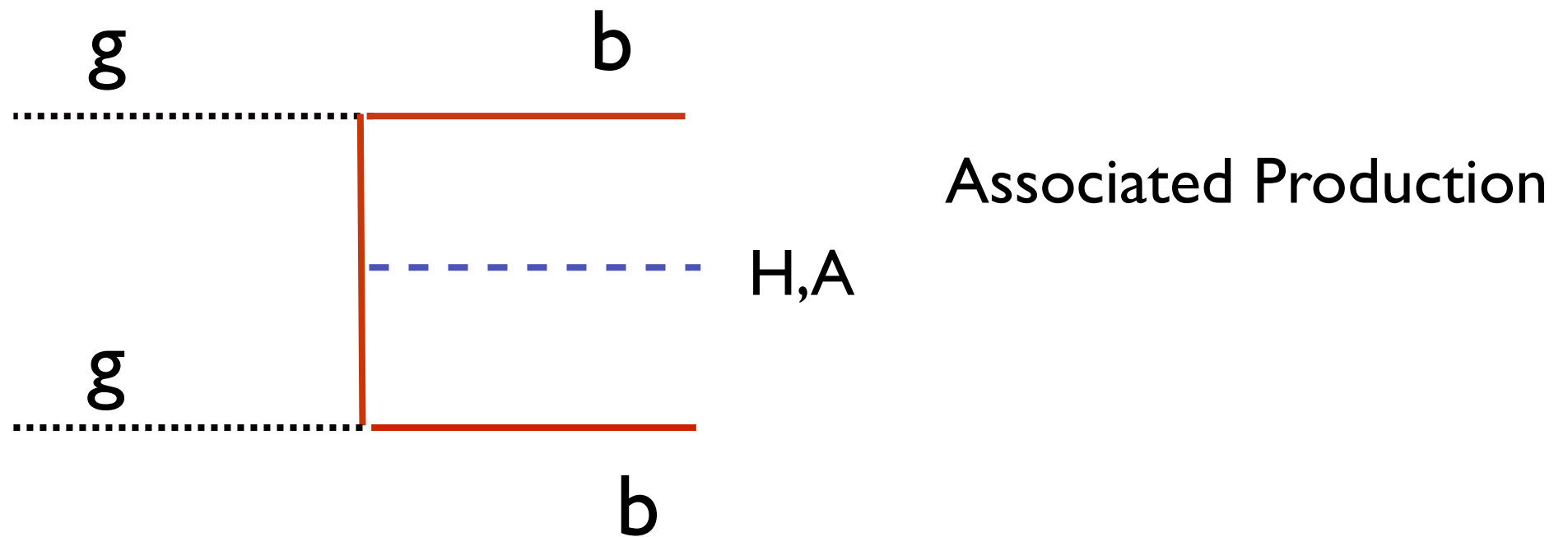
Values of the soft parameters larger than 250 GeV
tend to lead to vacuum stability problems

Small variations in BR [Hbb] induce
significant variations in the other Higgs BR's

Gluon fusion production rate can be varied for light stops

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan \beta}{(1 + \Delta_b)v}, \quad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan \beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G. Weiglein, C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \rightarrow b\bar{b}) \simeq \sigma(b\bar{b}A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \rightarrow A) \times BR(A \rightarrow \tau\tau) \simeq \sigma(b\bar{b}, gg \rightarrow A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by D.

North and M. Spira, arXiv:0808.0087

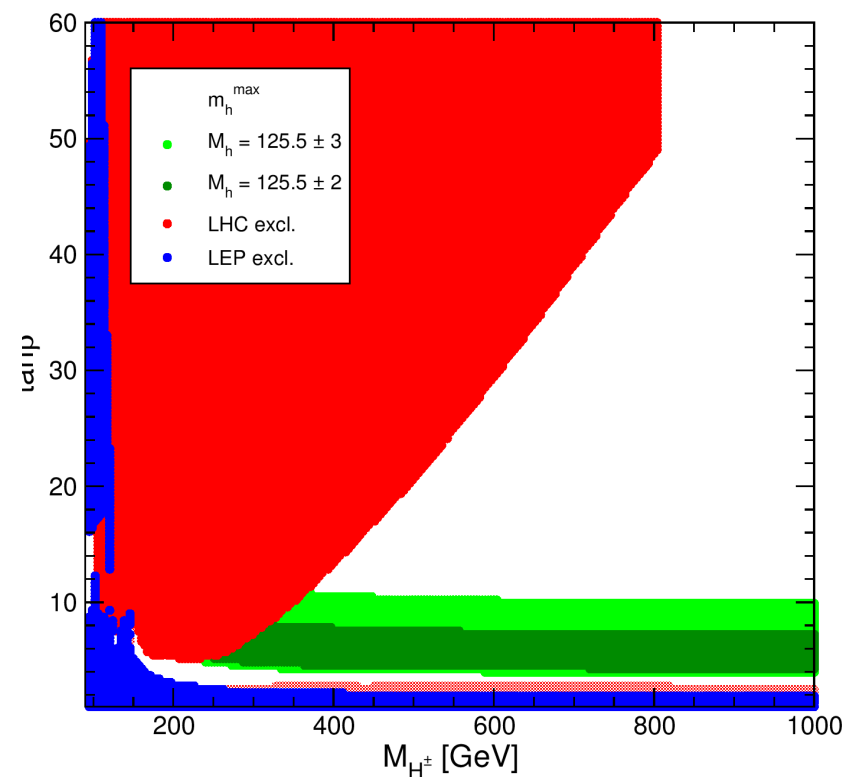
Further work by Mhulleitner, Rzehak and Spira, 0812.3815

Benchmark Scenarios after the Discovery of the 125 GeV Higgs

[M. Carena](#), [S. Heinemeyer](#), [O. Stål](#), [C.E.M. Wagner](#), [G. Weiglein](#),
[arXiv:1202.7033](#)

The m_h^{\max} scenario

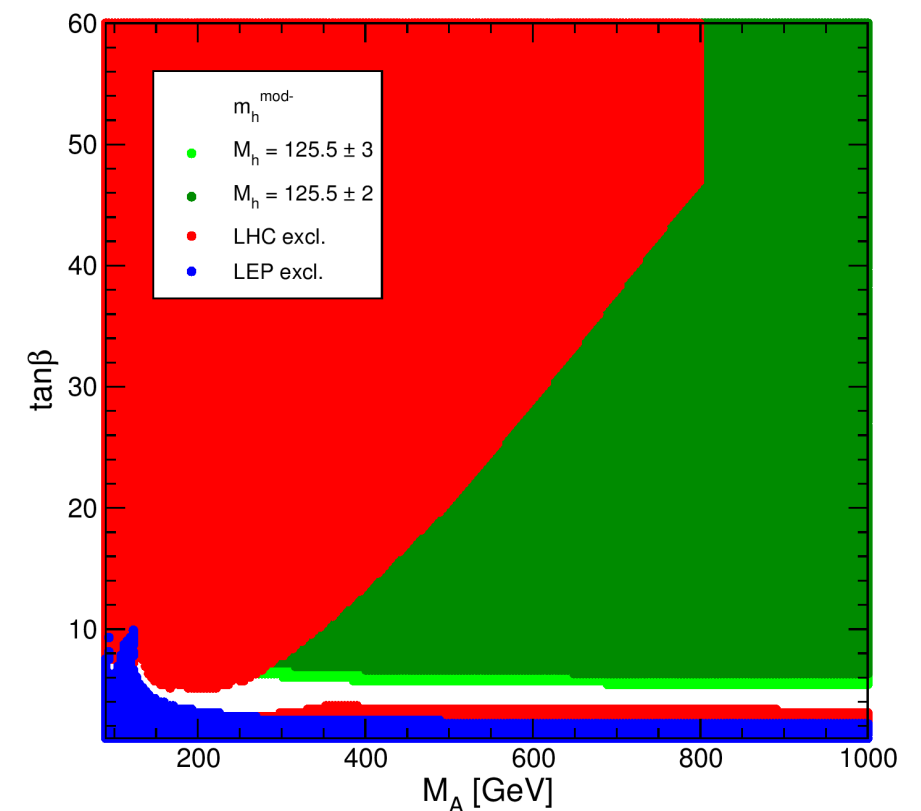
Gives the lowest value of $\tan(\beta)$ consistent with the measured Higgs mass



$$\begin{aligned} M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 200 \text{ GeV}, \\ M_2 &= 200 \text{ GeV}, \\ X_t^{\text{OS}} &= 2 M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= \sqrt{6} M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \end{aligned}$$

The m_h^{mod} scenario

Moderate values of the stop mixing allow for consistency with the Higgs mass value in a broad region of the m_A - $\tan(\beta)$ plane

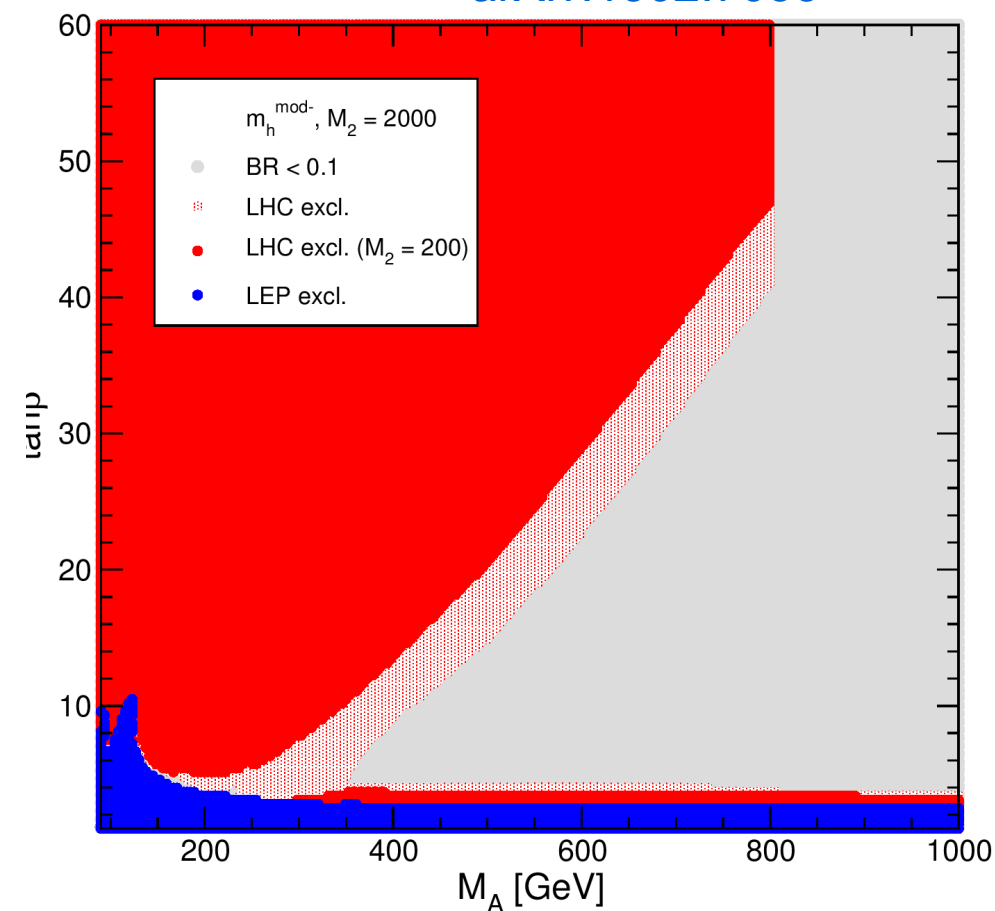
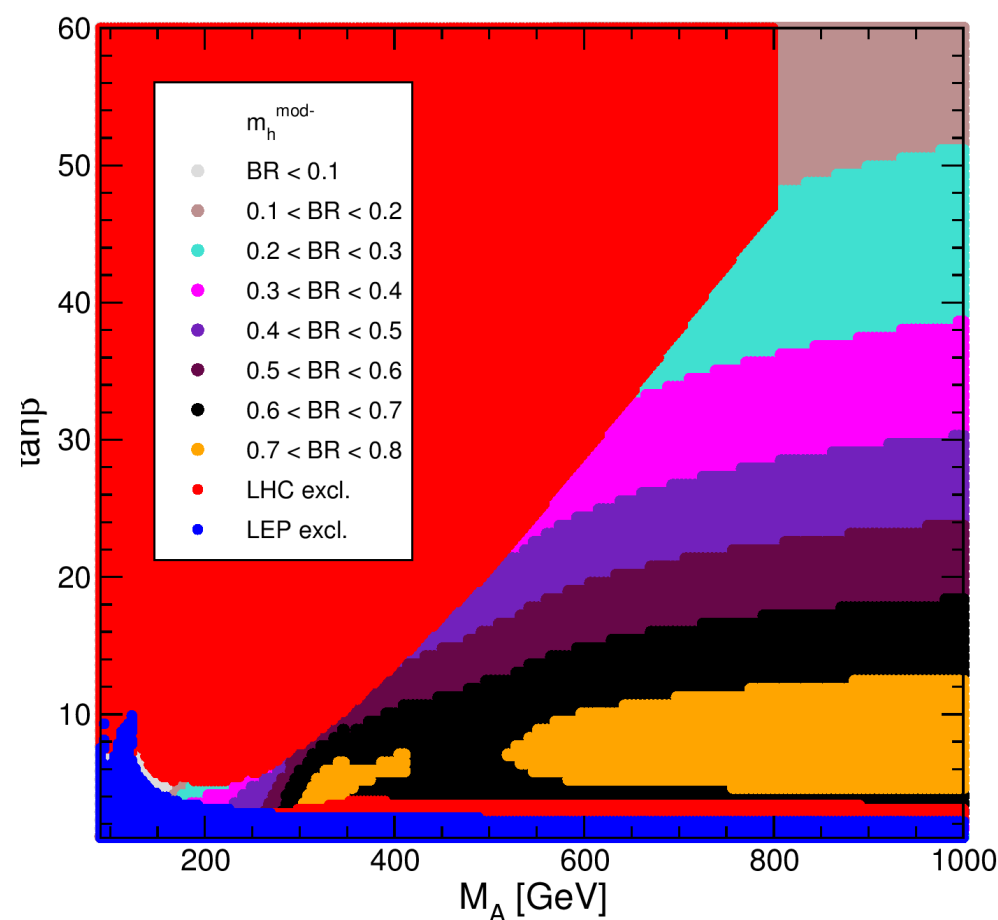


$$\begin{aligned} M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 200 \text{ GeV}, \\ M_2 &= 200 \text{ GeV}, \\ X_t^{\text{OS}} &= 1.5 M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 1.6 M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \end{aligned}$$

Decays of the non-standard Higgs bosons into EWKinOs in the

m_h^{mod} scenario

[M. Carena](#), [S. Heinemeyer](#), [O. Stål](#),
[C.E.M. Wagner](#), [G. Weiglein](#),
[arXiv:1302.7033](#)



Reach of non-standard Higgs bosons in tau decays modified
Opportunity for dedicated search of these decays.

Also $BR(H \rightarrow hh)$ may become important
for small values of $\tan\beta$

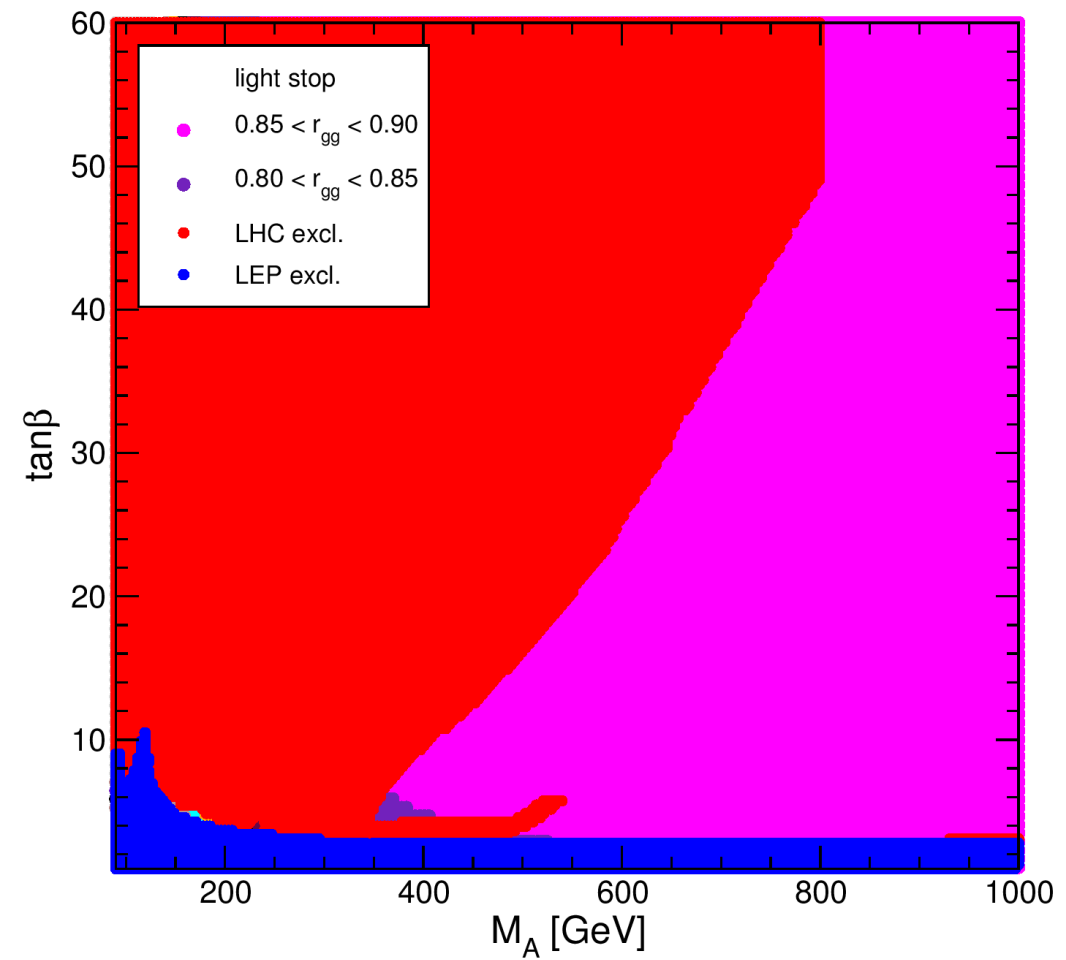
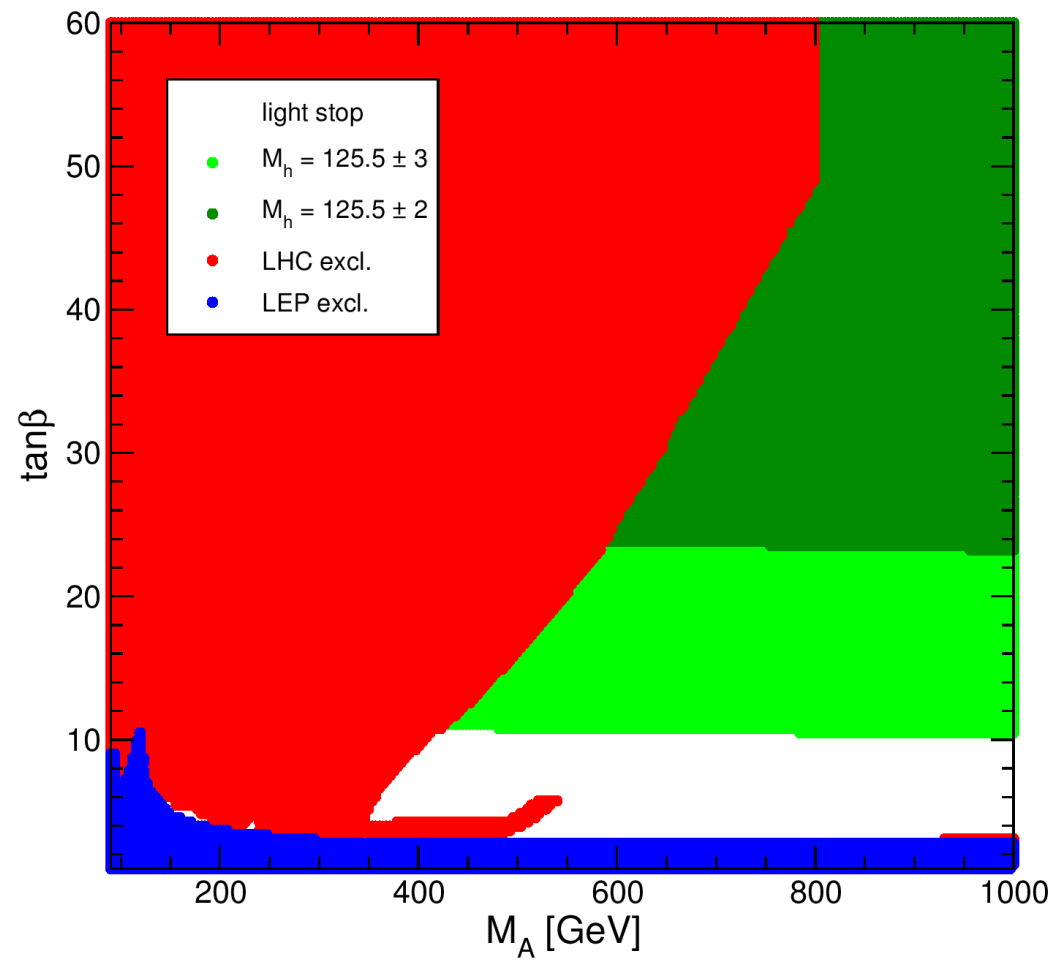
The Light Stop Scenario

Stop mixing large, lightest stop mass of order 320 GeV.

Heaviest stop mass of order 650 GeV.

Reduction of the gluon fusion process rate.

$$\delta\mathcal{A}_{hgg}/\mathcal{A}_{hgg}^{\text{SM}} \simeq \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} (m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2)$$



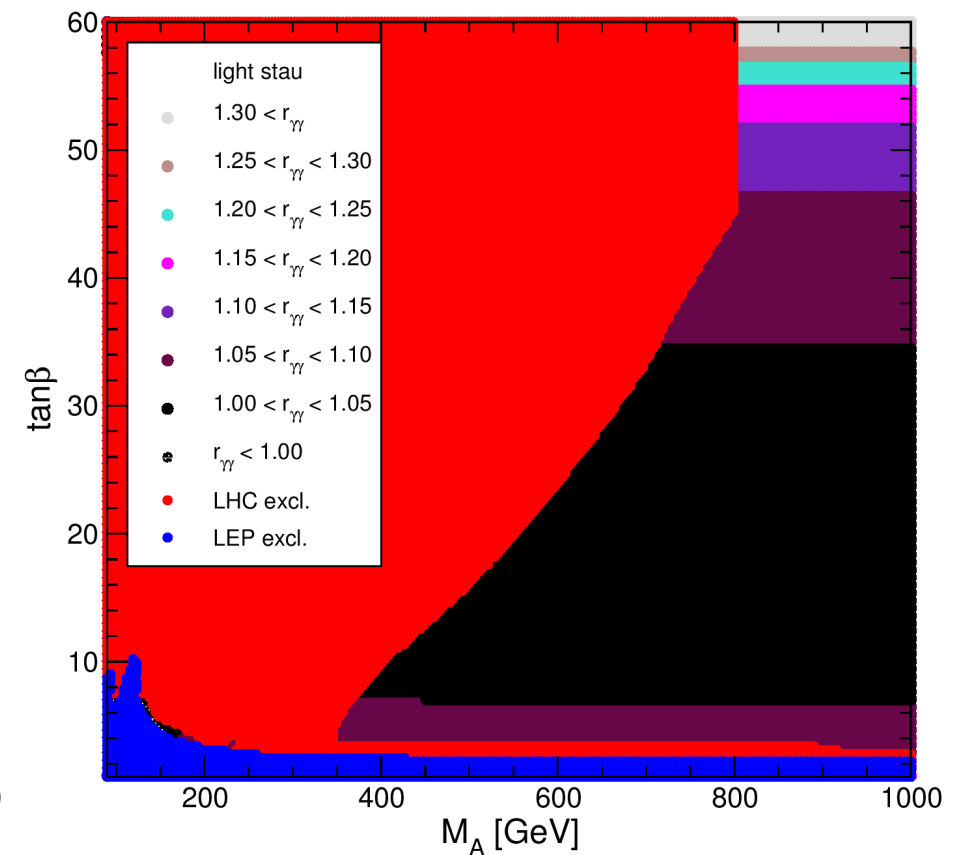
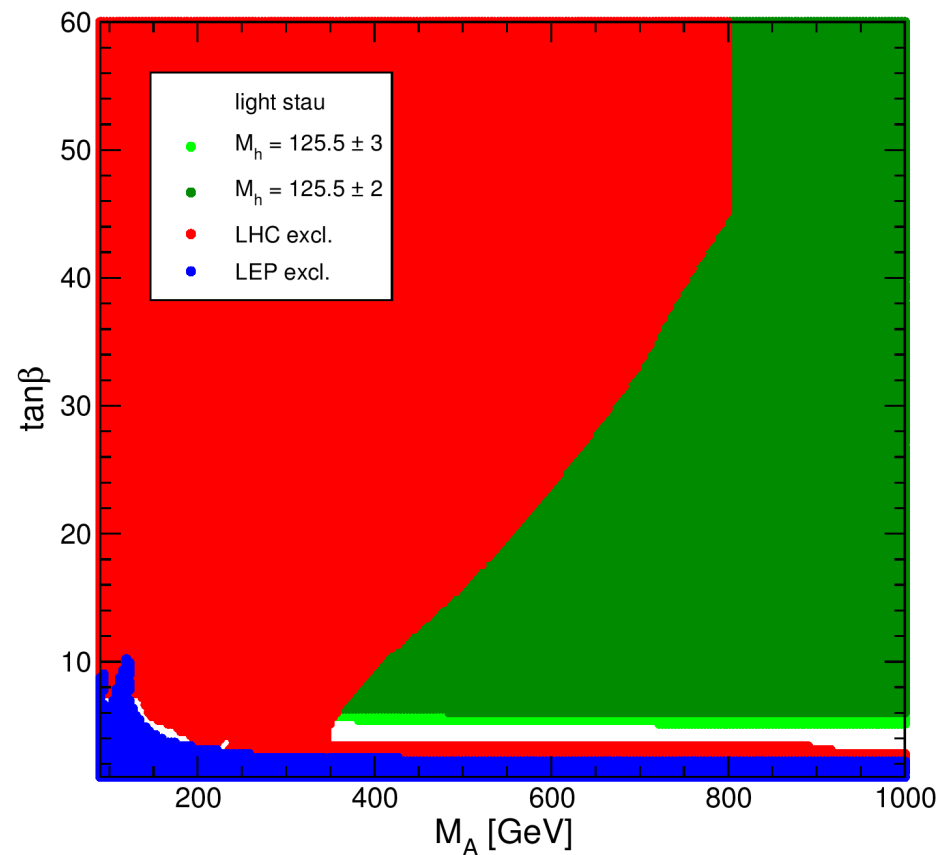
$$\begin{aligned} M_{\text{SUSY}} &= 500 \text{ GeV}, \\ \mu &= 350 \text{ GeV}, \\ M_2 &= 350 \text{ GeV}, \end{aligned}$$

$$\begin{aligned} X_t^{\text{OS}} &= 2.0 M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 2.2 M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_t = A_\tau, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \end{aligned}$$

The Light Stau Scenario

Enhancement of diphoton decay rate at large values of $\tan(\beta)$.

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}_{h\gamma\gamma}^{\text{SM}} \simeq -\frac{2 m_\tau^2}{39 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} (m_{\tilde{\tau}_1}^2 + m_{\tilde{\tau}_2}^2 - X_\tau^2)$$

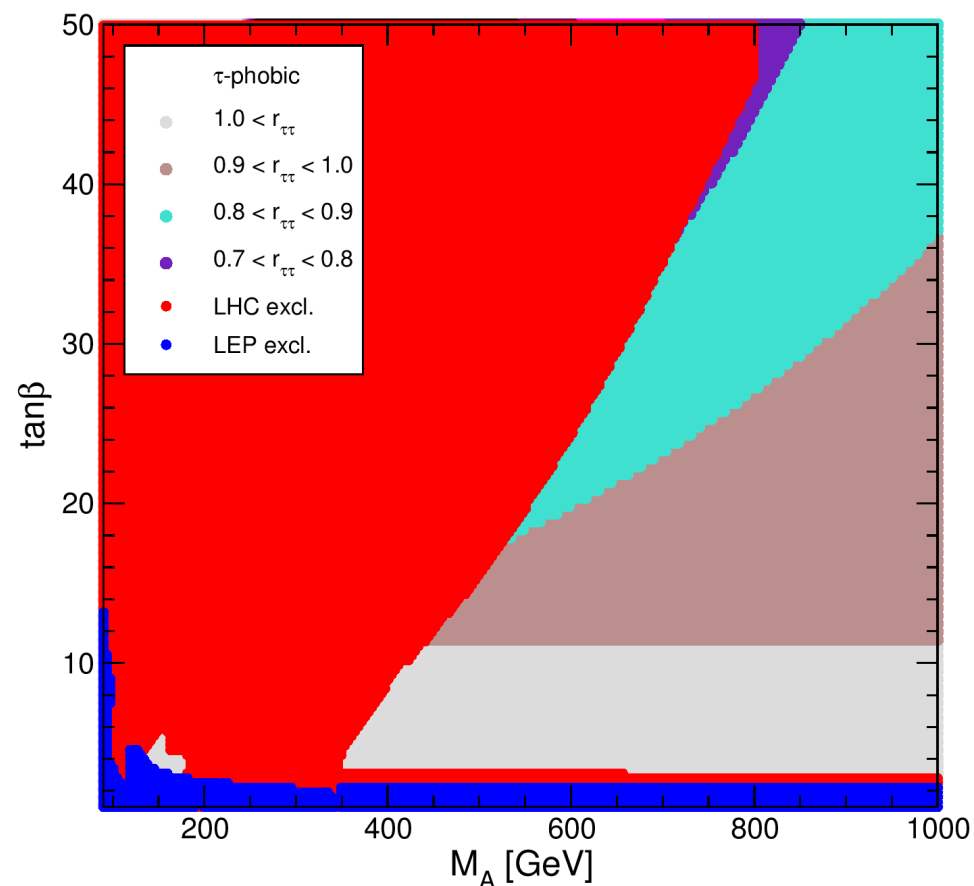
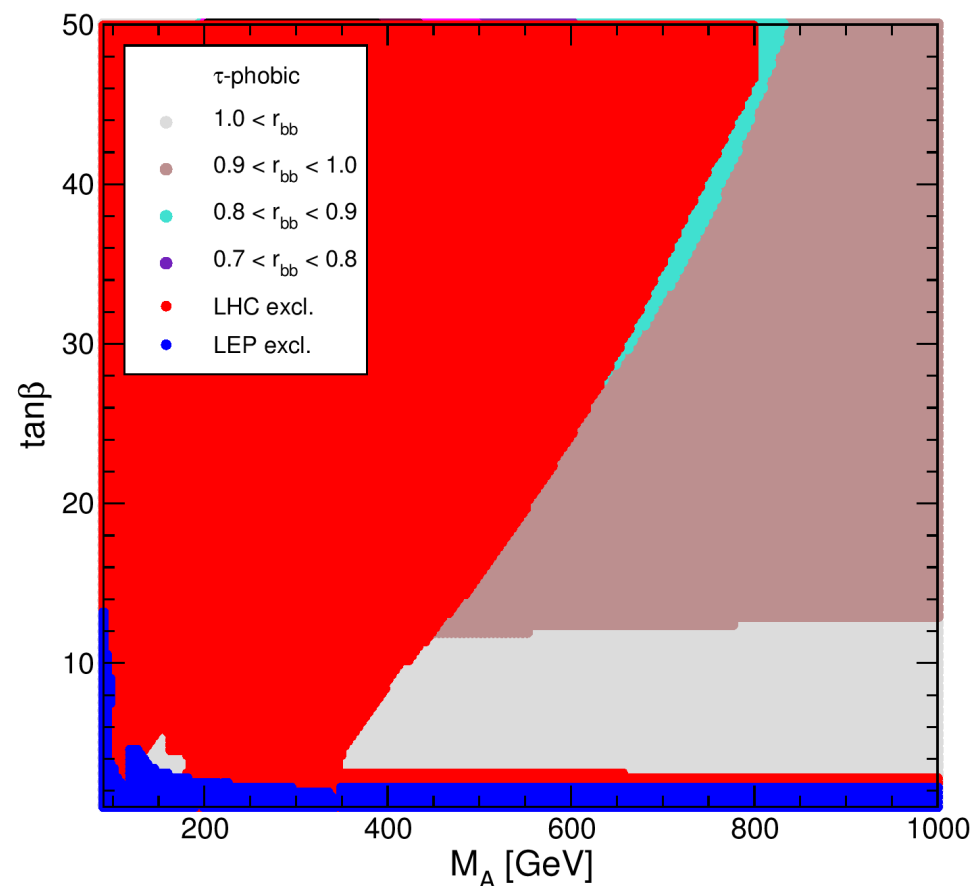


$$\begin{aligned} M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 500 \text{ GeV}, \\ \mu &= 450 \text{ GeV } (\Delta_\tau \text{ calculation}), \\ M_2 &= 200 \text{ GeV}, \\ M_2 &= 400 \text{ GeV } (\Delta_\tau \text{ calculation}), \end{aligned}$$

$$\begin{aligned} X_t^{\text{OS}} &= 1.6 M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 1.7 M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_t, \\ A_\tau &= 0, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 245 \text{ GeV}, \\ M_{\tilde{l}_3} &= 250 \text{ GeV } (\Delta_\tau \text{ calculation}). \end{aligned}$$

The τ -phobic Higgs scenario

Suppression of down-type fermion couplings to the Higgs due to Higgs mixing effects. Staus play a relevant role. Decays into staus relevant for heavy non-standard Higgs bosons.



$$\begin{aligned}
 M_{\text{SUSY}} &= 1500 \text{ GeV}, \\
 \mu &= 2000 \text{ GeV}, \\
 M_2 &= 200 \text{ GeV}, \\
 X_t^{\text{OS}} &= 2.45 M_{\text{SUSY}} \text{ (FD calculation)}, \\
 X_t^{\overline{\text{MS}}} &= 2.9 M_{\text{SUSY}} \text{ (RG calculation)}, \\
 A_b &= A_\tau = A_t, \\
 m_{\tilde{g}} &= 1500 \text{ GeV}, \\
 M_{\tilde{l}_3} &= 500 \text{ GeV}.
 \end{aligned}$$

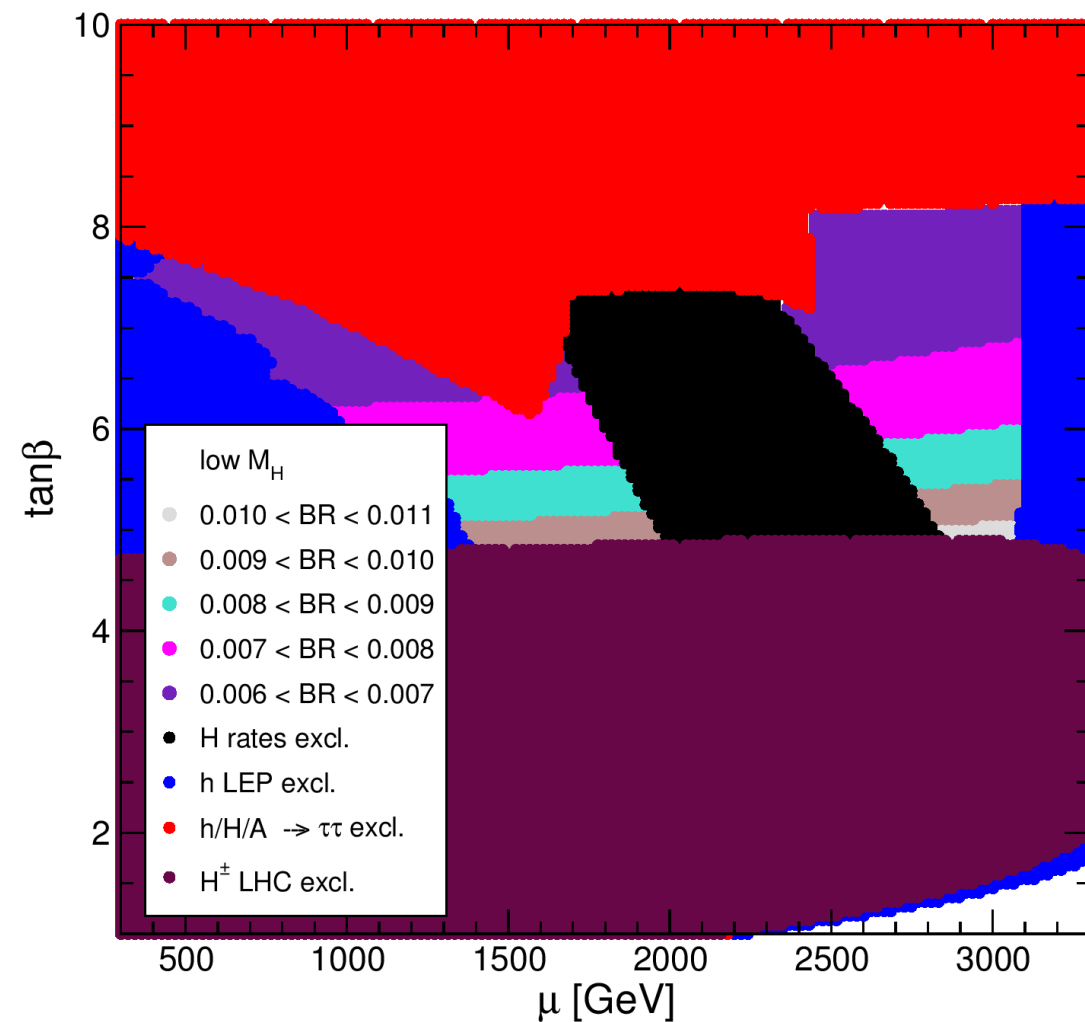
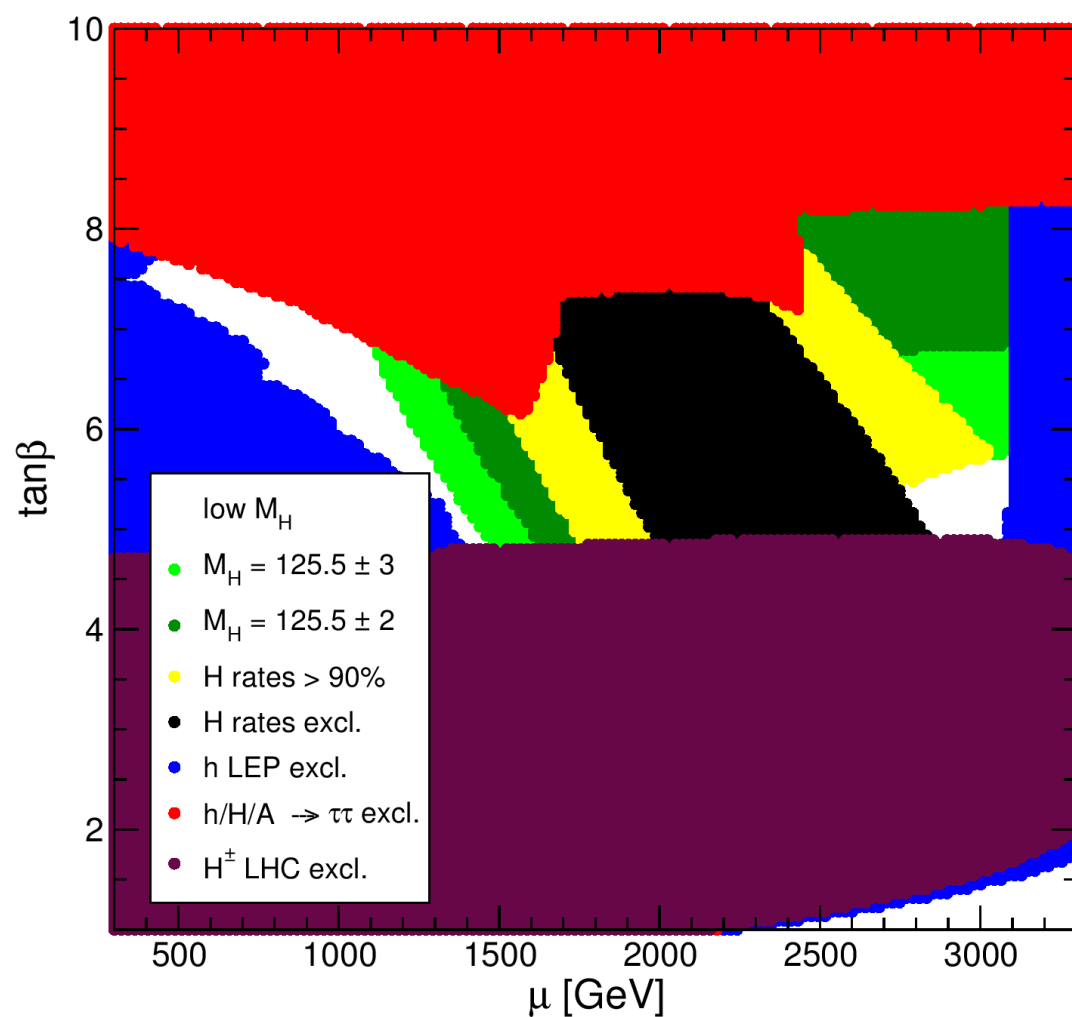
[M. Carena](#), [S. Heinemeyer](#), [O. Stål](#),
[C.E.M. Wagner](#), [G. Weiglein](#),
[arXiv:1302.7033](#)

$$\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta} \frac{\mu \bar{A}_t}{M_{\text{SUSY}}^2} \left[\frac{A_t \bar{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}$$

The low- M_H scenario

Heavy CP-even Higgs boson is SM-like

[M. Carena](#), [S. Heinemeyer](#), [O. Stål](#), [C.E.M. Wagner](#), [G. Weiglein](#), arXiv:1302.7033



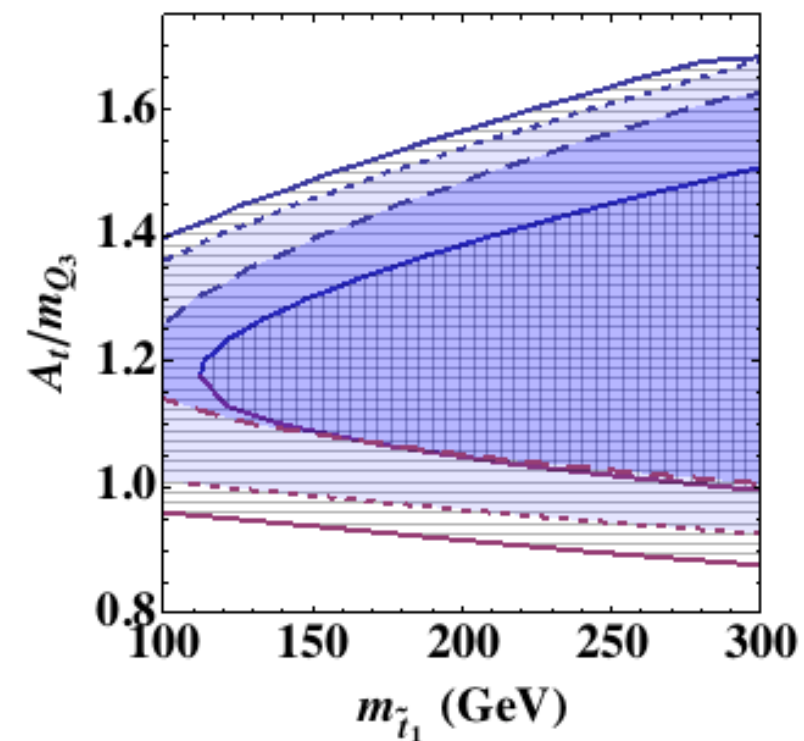
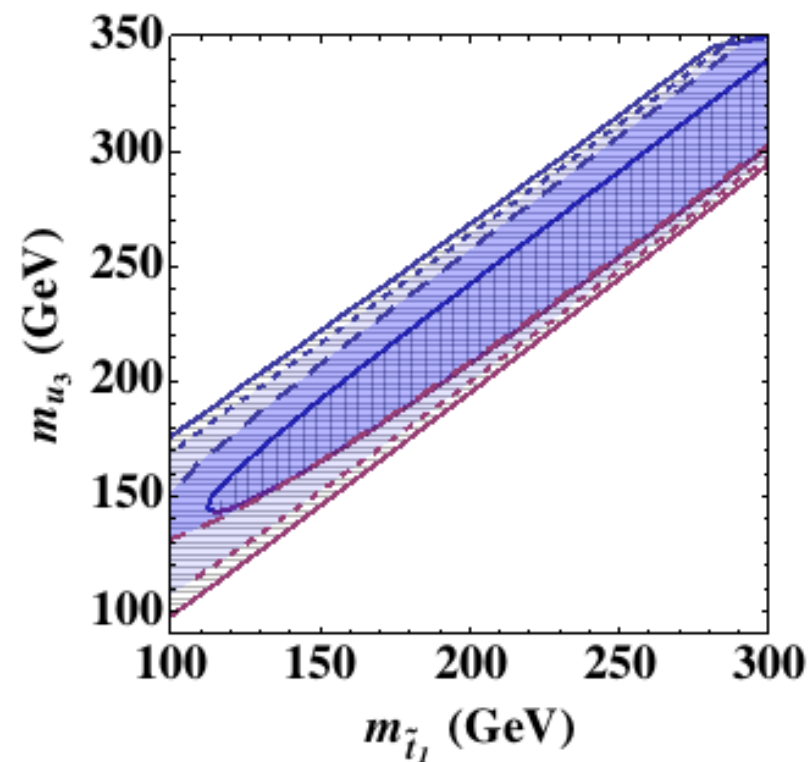
$$\begin{aligned}
 M_A &= 110 \text{ GeV}, \\
 M_{\text{SUSY}} &= 1500 \text{ GeV}, \\
 M_2 &= 200 \text{ GeV}, \\
 X_t^{\text{OS}} &= 2.45 M_{\text{SUSY}} \text{ (FD calculation)}, \\
 X_t^{\overline{\text{MS}}} &= 2.9 M_{\text{SUSY}} \text{ (RG calculation)}, \\
 A_b &= A_\tau = A_t, \\
 m_{\tilde{g}} &= 1500 \text{ GeV}, \\
 M_{\tilde{l}_3} &= 1000 \text{ GeV}.
 \end{aligned}$$

Top decay into charged Higgs bosons at the edge of being tested.

Whole parameter space consistent with this scenario may be probed in the near future

Light Stops, Light Staus and the 125 GeV Higgs

Cases	$\tan \beta$	$m_{\tilde{\tau}_1}$ (GeV)	m_{e_3} (GeV)	μ (GeV)	m_{Q_3} (TeV)	A_τ (TeV)	m_A (TeV)
(a) Shaded dashed	70	95	250	380	2	0	2
(b) Shaded dotted	70	95	230	320	2	1	1
(c) Horizontal hatch	105	95	240	225	2	1	1
(d) Vertical hatch	70	100	300	575	3	1.5	1

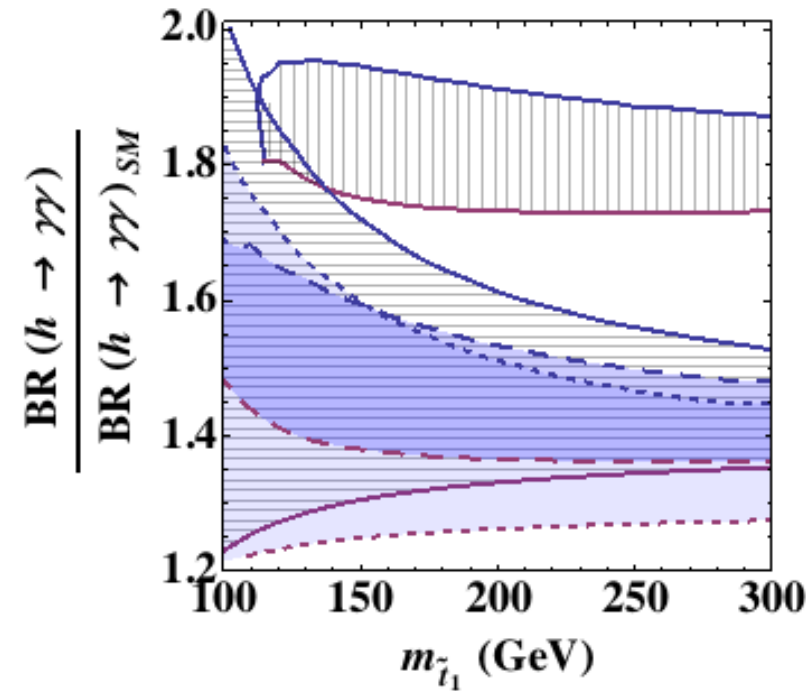
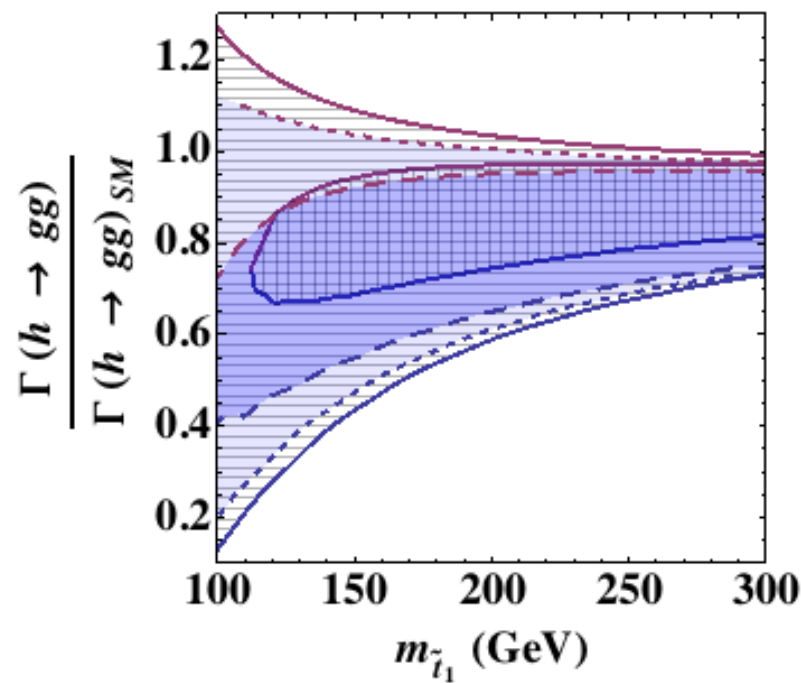


(a) to (c) : Consistent with vacuum stability constraints

M. Carena, S. Gori, I. Low, N. Shah, C.W., arXiv:1211.6136

Variation of Production Cross sections and Decay Rates

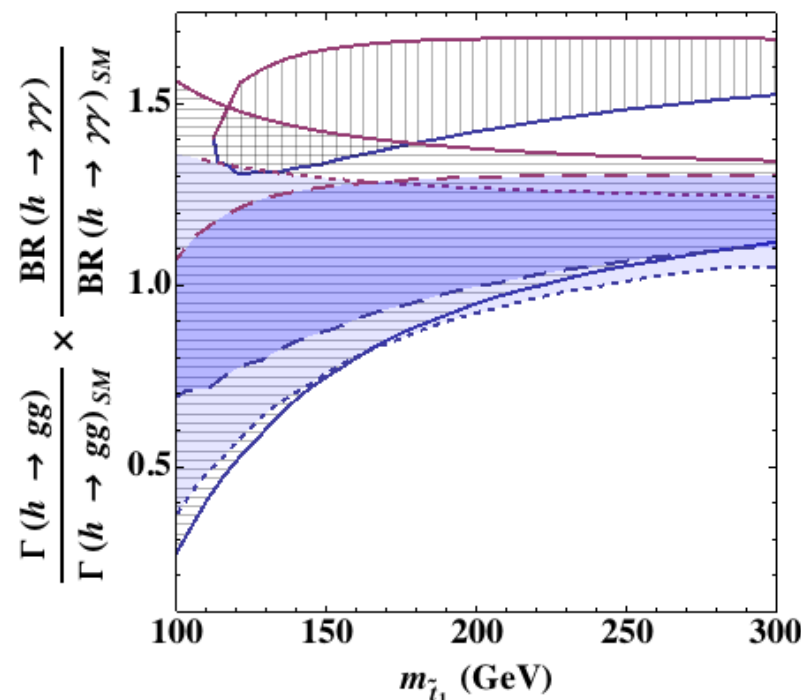
M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](https://arxiv.org/abs/1303.4414)



$$\delta \mathcal{A}_{hgg} / \mathcal{A}_{hgg}^{\text{SM}} \simeq \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} (m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2)$$

$$\delta \mathcal{A}_{h\gamma\gamma} / \mathcal{A}_{h\gamma\gamma}^{\text{SM}} \simeq -\frac{2 m_\tau^2}{39 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} (m_{\tilde{\tau}_1}^2 + m_{\tilde{\tau}_2}^2 - X_\tau^2)$$

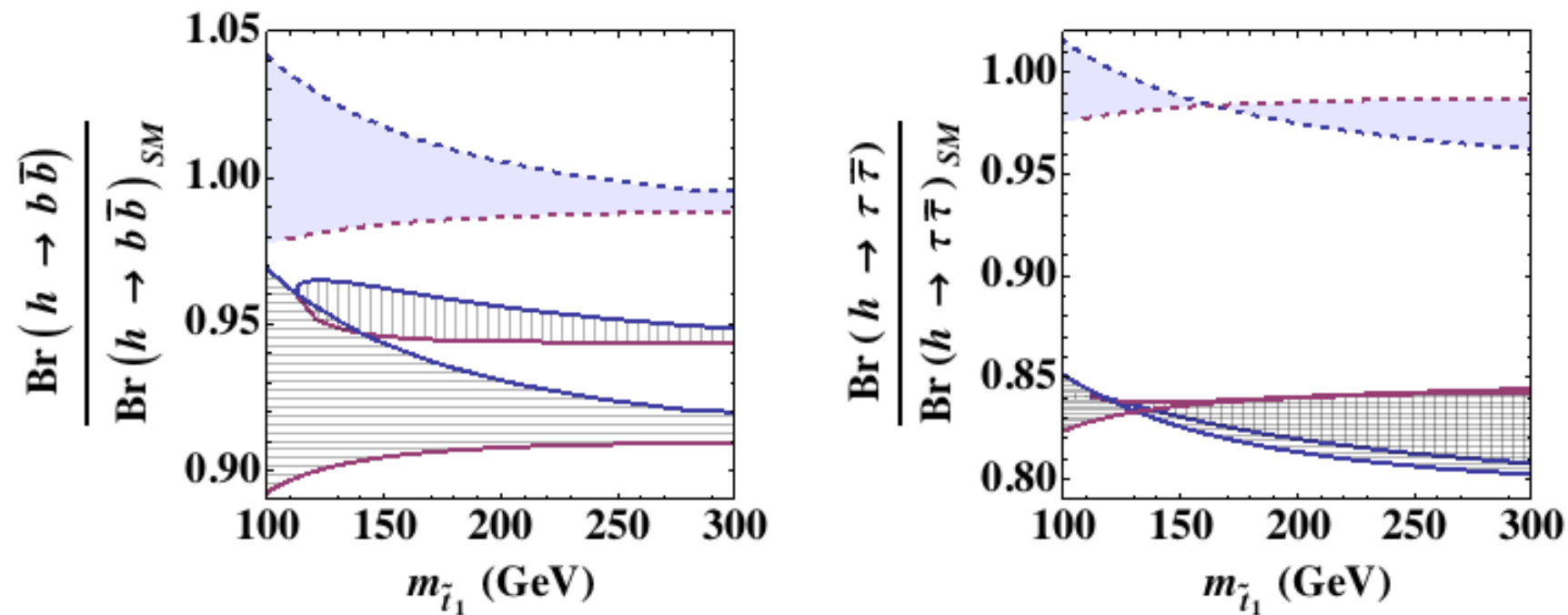
$$m_\tau = 95 \text{ GeV}$$



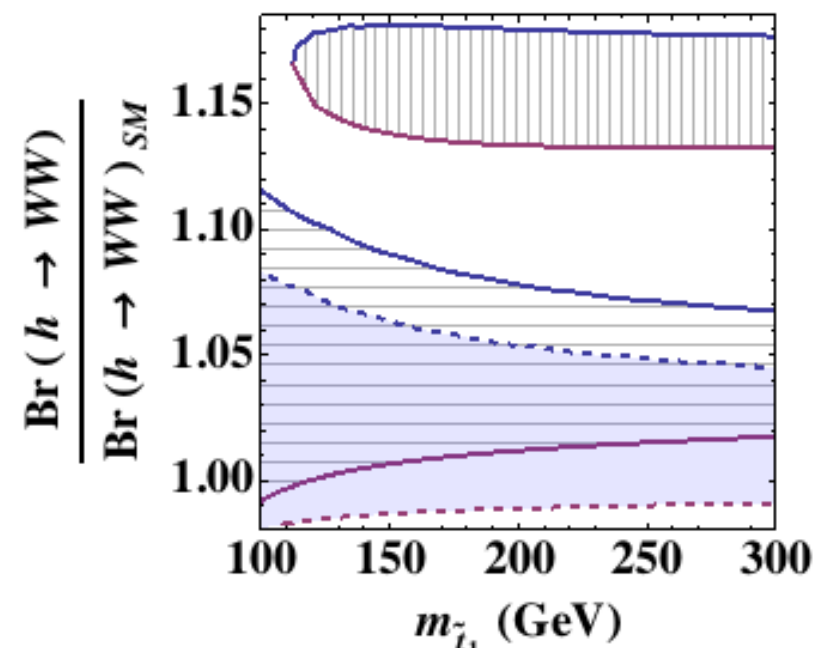
Light Staus can enhance the diphoton decay width
 Light stops can either enhance or suppress gluon coupling
 Combination can lead to large variations of production in
 both gluon fusion and weak boson fusion (ratios of
 branching ratios)

Coupling to Fermions and Weak Gauge Bosons

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](https://arxiv.org/abs/1303.4414)



(iii)



Impact of Light staus on heavy Higgs Boson Searches

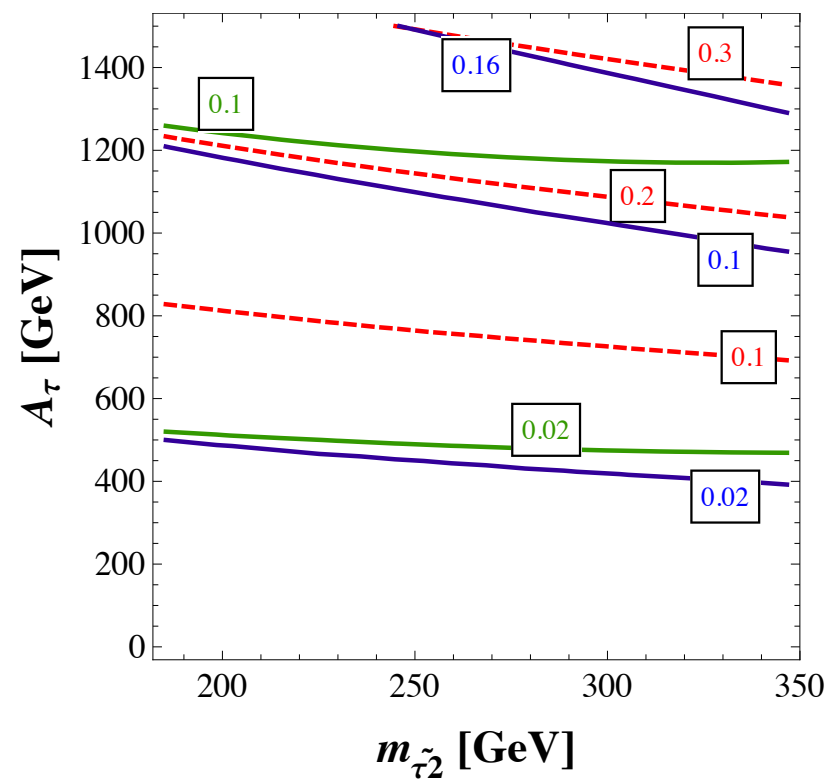
M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](#)

- Previous analysis performed under the assumption of no additional decays apart from the ones into bottom-quarks and tau-leptons.
- Light staus can lead to relevant extra contributions to the decay width.
- For large values of $A\tau$, the non-standard Higgs bosons couple strongly to staus at large $\tan\beta$.
- The additional width of the Higgs bosons leads to a reduction in the branching ratios into both bottoms and taus, and make searches more challenging.
- Searches for staus in decays of non-standard Higgs bosons should be also considered.

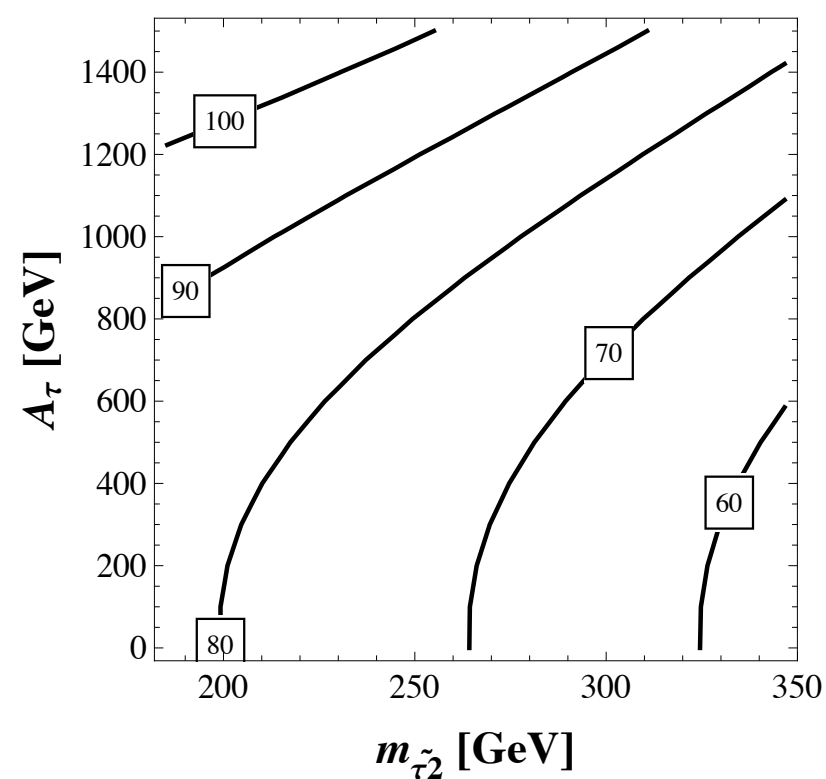
Branching Ratios and Widths of Non-Standard Higgs Decays into Staus

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](https://arxiv.org/abs/1303.4414)

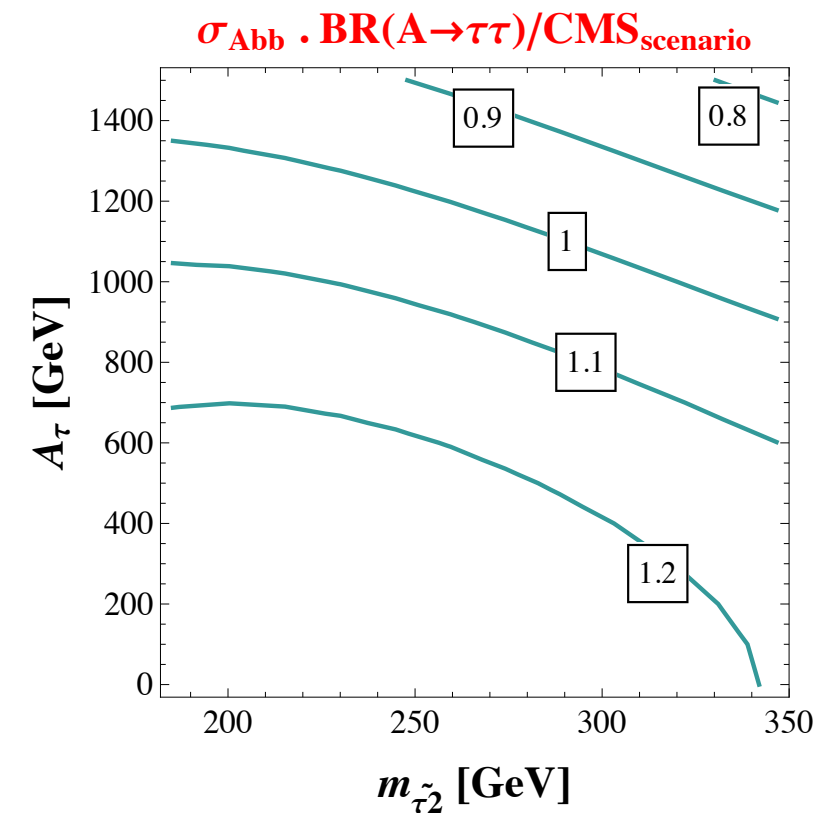
$$\sigma(pp \rightarrow (H, A) \rightarrow \tau^+ \tau^-) \propto \frac{m_b^2 \tan^2 \beta}{\left[\left(3 \frac{m_b^2}{m_\tau^2} + \frac{(M_W^2 + M_Z^2)(1 + \Delta_b)^2}{m_\tau^2 \tan^2 \beta} \right) (1 + \Delta_\tau)^2 + (1 + \Delta_b)^2 \left(1 + \frac{A_\tau^2}{m_A^2} \right) \right]}$$



Decay branching
ratio of heavy non-standard
Higgs boson to staus



Total heavy Higgs
boson width



Decay branching
ratio into taus,
compared to the
mhmax scenario.

Conclusions

- Resonance discovered at the LHC has properties consistent with SM Higgs ones.
- Precise production rates and branching ratios may be affected by new physics. As an example, we have studied the MSSM case
- This model has a rich phenomenology that can lead to large variations of the couplings and to new related signatures at colliders.
- Higgs couplings may give hints of the realization of the MSSM.
- Third generation sfermions play a very relevant role and, if they are light, they can have a relevant impact on the Higgs phenomenology
- Non-standard Higgs bosons, if not too-heavy, can modify the light CP-even properties and also provide new handles of searches for third generation sfermions and electroweakinos.
- Let's look forward for new LHC data !

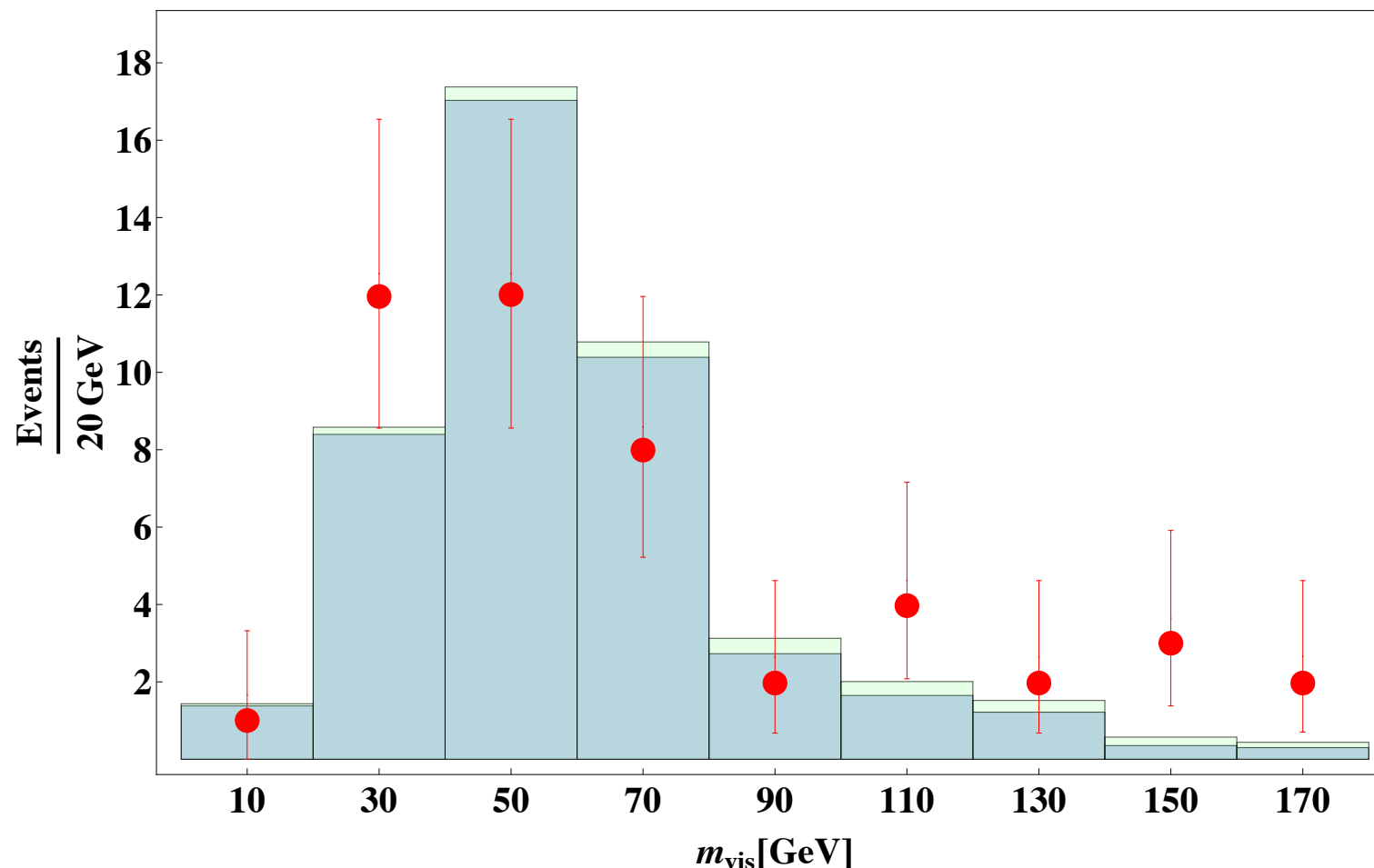
Searches for staus in associated production with sneutrinos.

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](https://arxiv.org/abs/1303.4414)

Final State in $pp \rightarrow Wh$, followed by $h \rightarrow \tau^+ \tau^-$ is similar to the one in

$pp \rightarrow \tilde{\tau} \tilde{\nu}_\tau$, followed by $\tilde{\nu}_\tau \rightarrow \tilde{\tau} + \chi_1^0$.

Look for leptonic decay of the W, and one hadronic and one leptonic tau decay. Same selection cuts as in the Higgs search analysis.



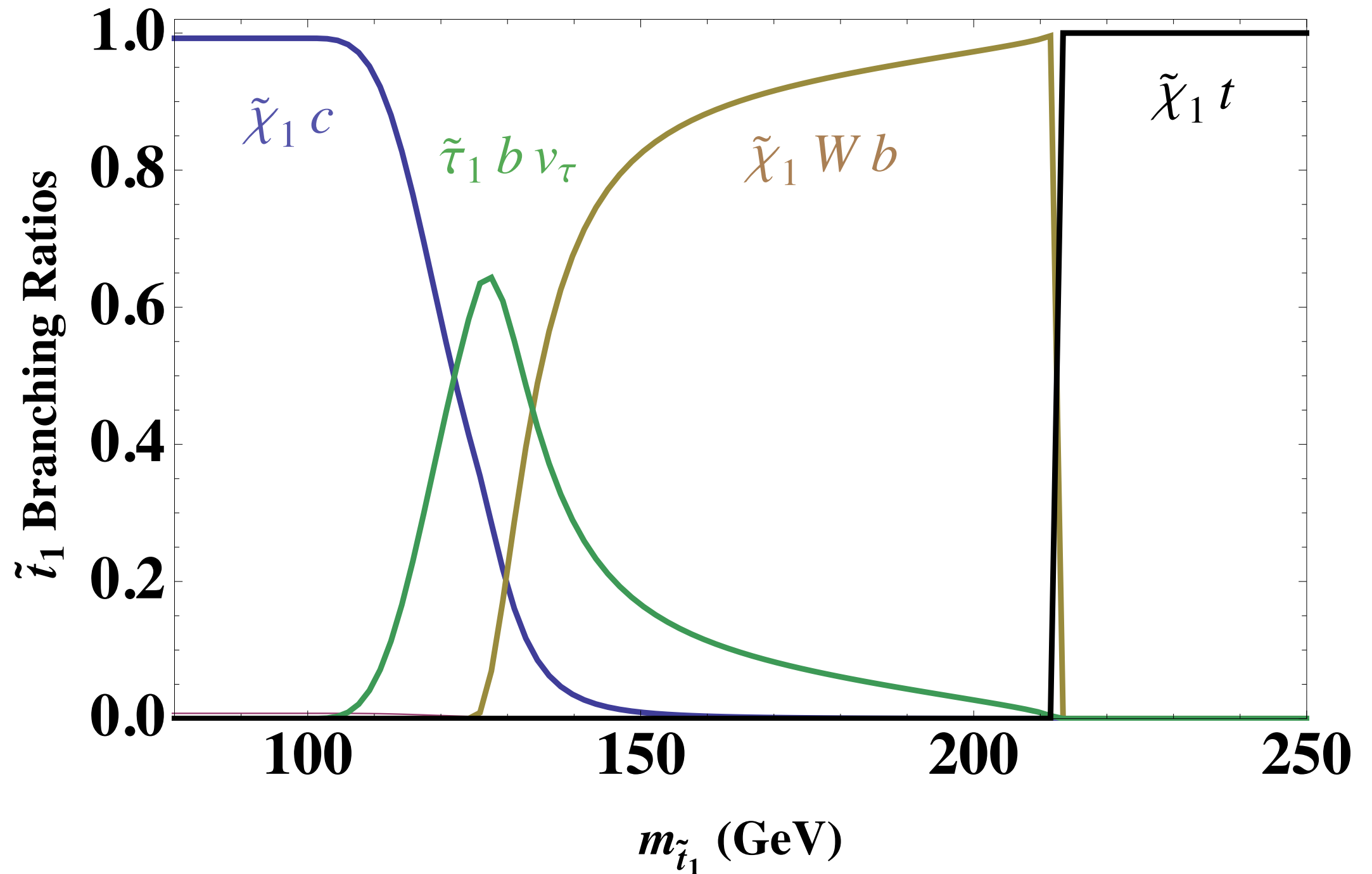
Cut in visible mass increase signal to background ratio, but very low statistics. Dedicated search with optimized selection cuts should be performed.

Light Stop Searches

- Light stops, mainly right handed, may be present without affecting the Higgs mass predictions and without affecting precision electroweak measurements.
- If present, they have an impact on both gluon fusion cross section as well as in $\gamma\gamma$ Higgs decay width. There are strong direct search constraints.
- Three body decay into staus may become the dominant stop decay mode, when three body decay into a neutralino, a W and a b is closed.
- For a neutralino mass of about 40 to 50 GeV, this happens for stop masses of about 130 GeV.

Stop Branching Ratios in Light Stau Scenario

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](#)



Apart from region close to top neutralino decay threshold, decays of stops into staus open new possibilities

Vacuum stability

For large values of the μ parameter and the tau Yukawa coupling, one can generate new charge breaking minima deeper than the electroweak minimum

$$V = \left| \mu \frac{h_u}{\sqrt{2}} - y_\tau \tilde{\tau}_L \tilde{\tau}_R \right|^2 + \frac{g_2^2}{8} \left(|\tilde{\tau}_L|^2 + \frac{h_u^2}{2} \right)^2 + \frac{g_1^2}{8} \left(|\tilde{\tau}_L|^2 - 2|\tilde{\tau}_R|^2 - \frac{h_u^2}{2} \right)^2 \\ + m_{H_u}^2 \frac{h_u^2}{2} + m_{L_3}^2 |\tilde{\tau}_L|^2 + m_{E_3}^2 |\tilde{\tau}_R|^2 + \frac{g_1^2 + g_2^2}{8} \delta_H \frac{h_u^4}{4} ,$$

This occurs in this improved tree-level potential, but also occurs in the full one-loop effective potential we shall analyze

Vacuum Stability

Electroweak Minimum is in general metastable in this scenario

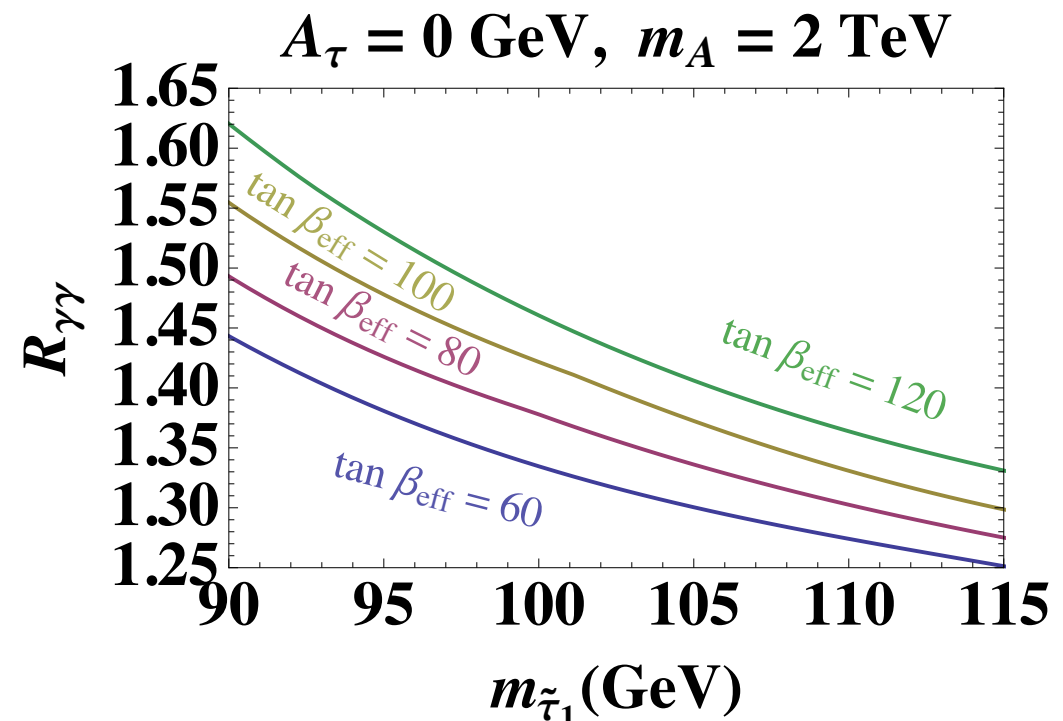
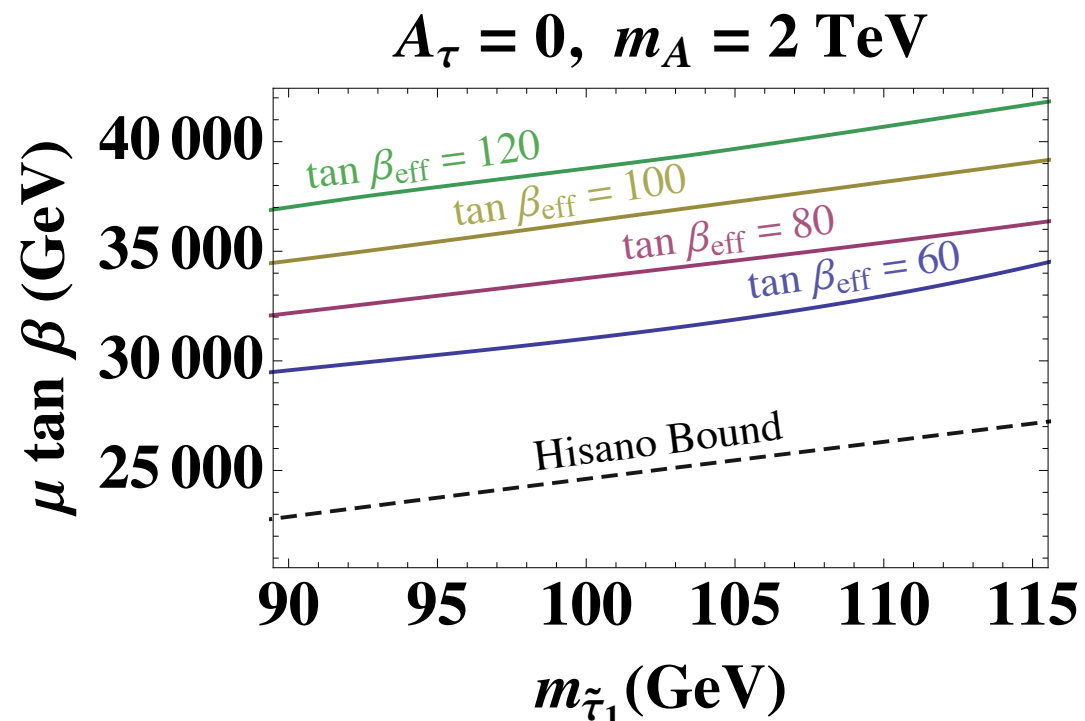
Hisano, Sugiyama'11

Metastability bound depends on $\tan(\beta)$

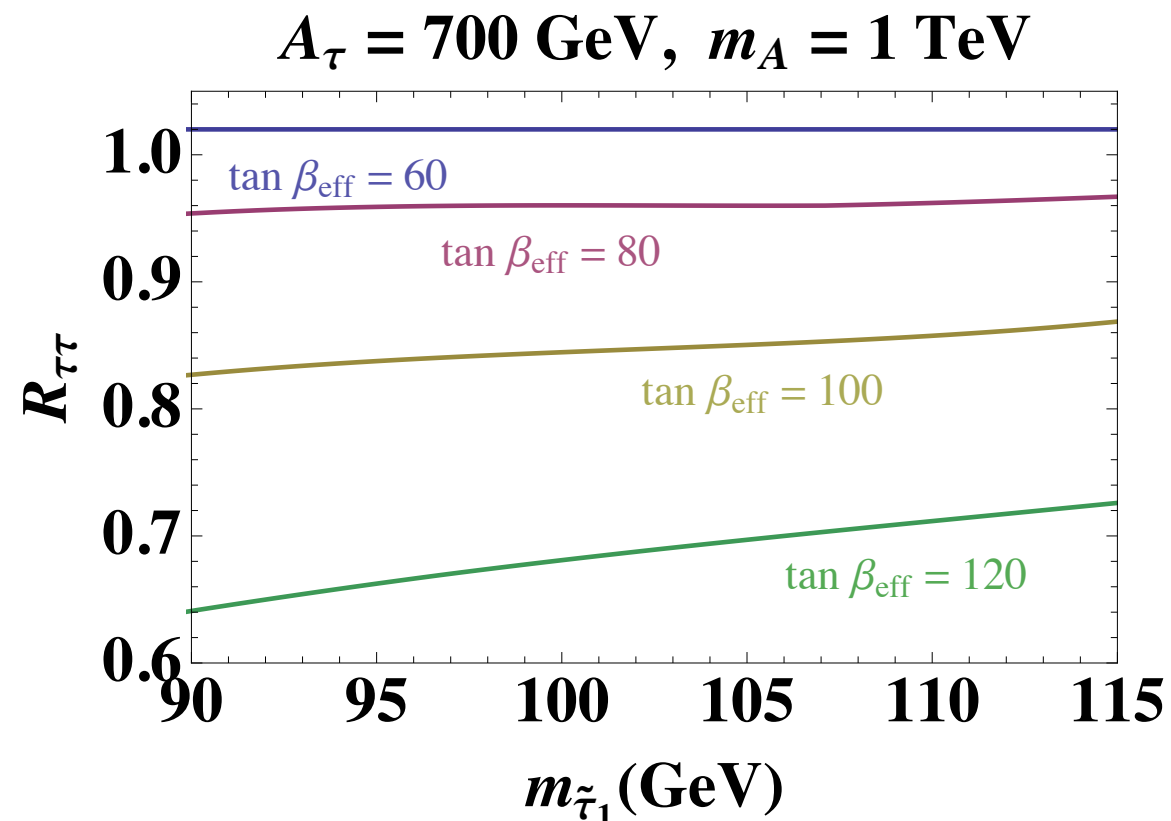
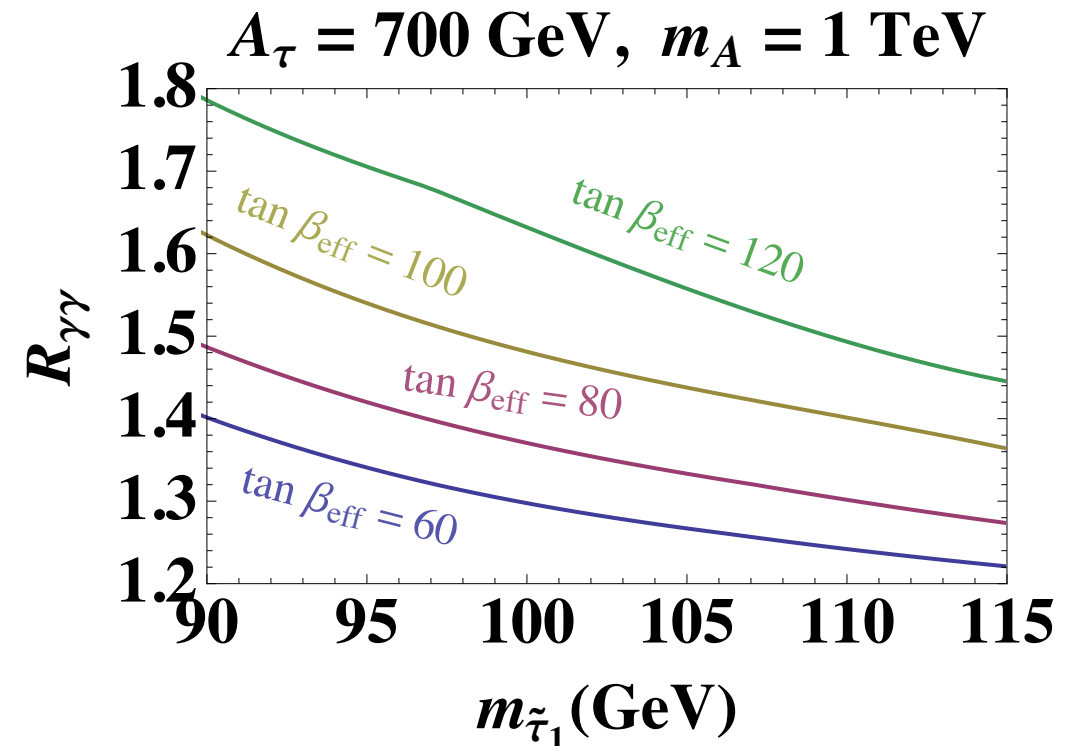
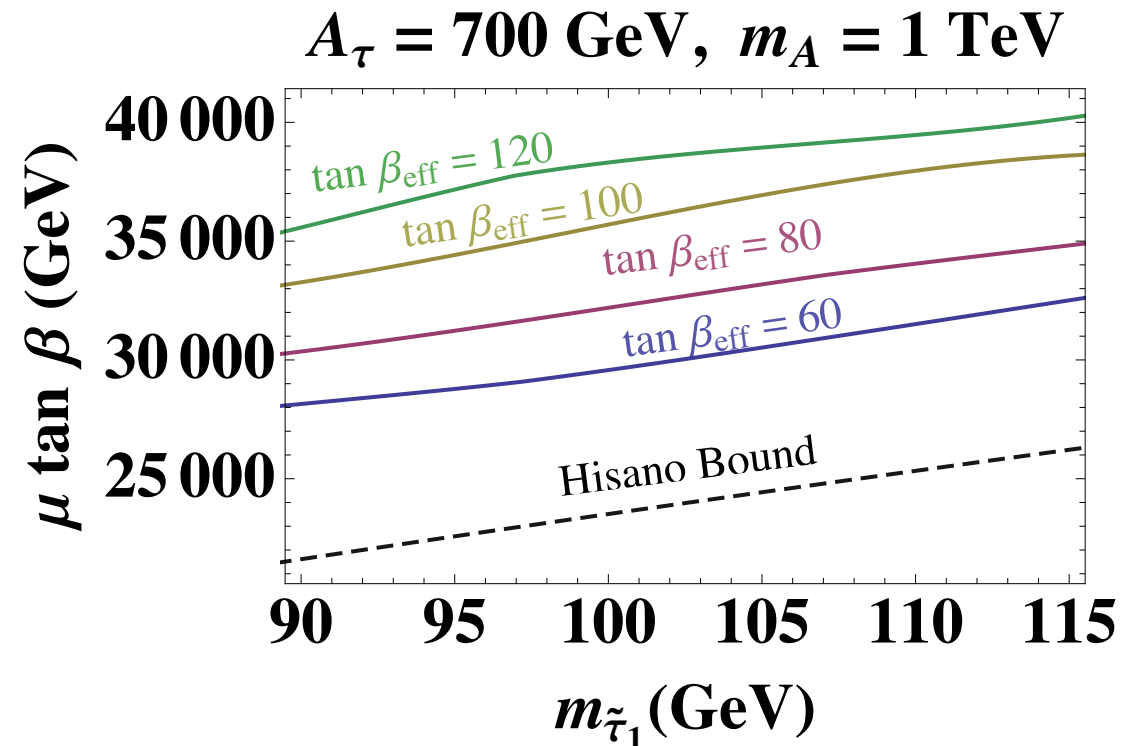
Effective values include one loop correction effects, and it is different for bottoms as for tau leptons. In the following, we refer to the tau one.

$$h_{b,\tau} \simeq \frac{m_b \tan \beta}{v(1 + \Delta_{b,\tau})}, \quad (\tan \beta_{\text{eff}})_{b,\tau} = \frac{\tan \beta}{(1 + \Delta_{b,\tau})}$$

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12



Inclusion of Mixing in the CP-even Higgs sector



[CPsuperH : arXiv:1208.2212](https://arxiv.org/abs/1208.2212)

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12

$$\frac{g_{hbb}}{g_{h\tau\tau}} = \frac{m_b(1 + \Delta_\tau)(1 - \Delta_b/(\tan \beta \tan \alpha))}{m_\tau(1 + \Delta_b)(1 - \Delta_\tau/(\tan \beta \tan \alpha))}.$$

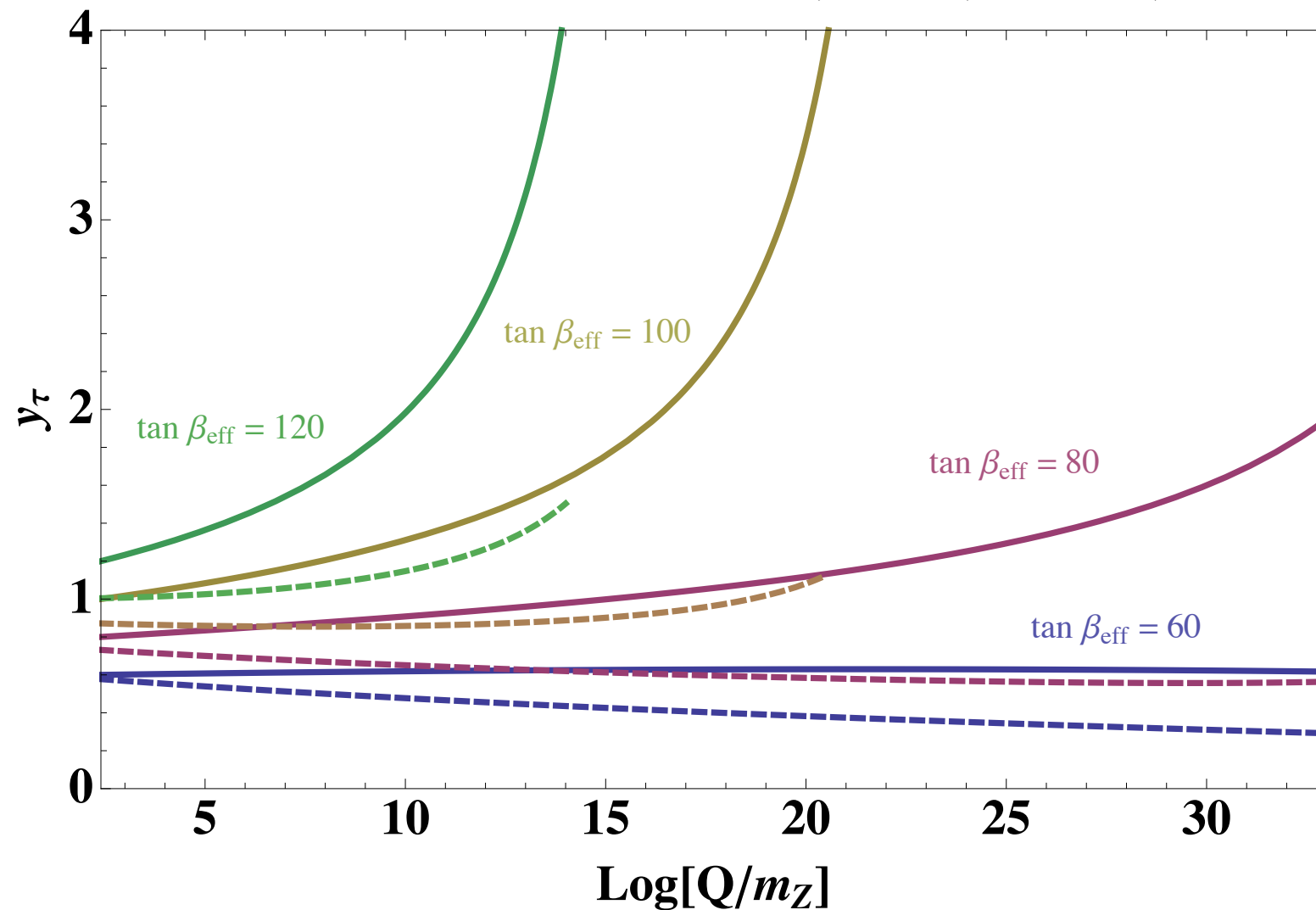
Branching ratio of decay into bottom quarks remain larger than 95 percent

Calculated with FeynHiggs (no Δ_τ but full one-loop corrections.)

New CPsuperH includes all Δ_f .
Leads to similar gamma gamma rates,
but slightly smaller τ suppressions.

Evolution of Yukawa Couplings

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W'12



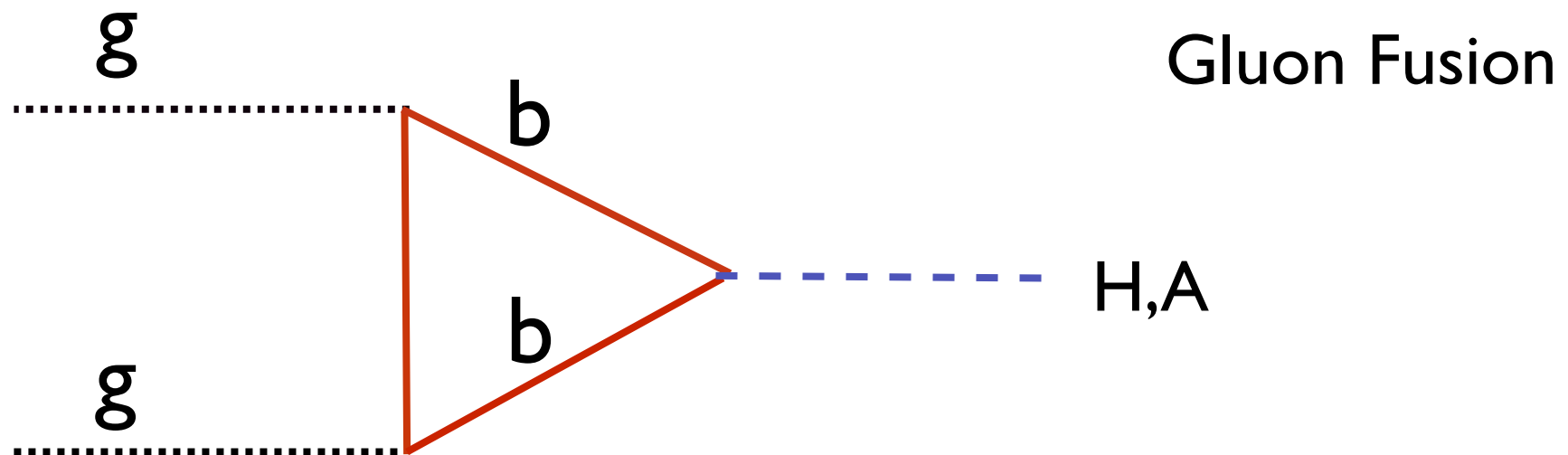
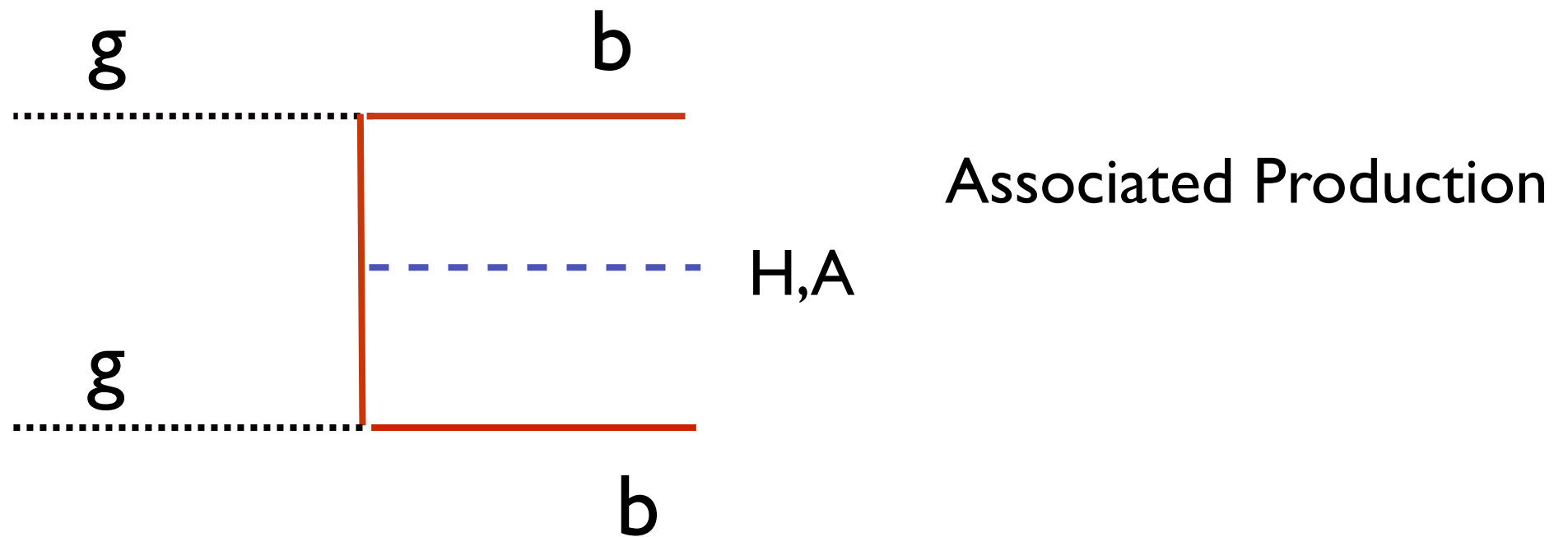
Large suppression of **Higgs decay into taus**, keeping metastability, may only be achieved at large values of the effective $\tan(\beta)$ of tau leptons.

Values of effective $\tan(\beta)$ larger than 90 imply the existence of a Landau pole before the GUT scale

An ultraviolet completion would be therefore necessary at high scales.

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan \beta}{(1 + \Delta_b)v}, \quad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan \beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G. Weiglein, C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \rightarrow b\bar{b}) \simeq \sigma(b\bar{b}A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \rightarrow A) \times BR(A \rightarrow \tau\tau) \simeq \sigma(b\bar{b}, gg \rightarrow A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by D.

North and M. Spira, arXiv:0808.0087

Further work by Mhulleitner, Rzehak and Spira, 0812.3815

